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PERFORMANCE OF ELECTRONIC BALLASTS AND OTHER NEW LIGHTING EQUIPMENT

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ABSTRACT

This study discusses parameters for selecting the most suitable auxiliary lighting device to operate and control gas-discharge lamps. The devices tested in this study include solid-state, fluorescent, and high-intensity discharge (HID) ballasts; current limiters; and dynamic lighting controls. They have been evaluated when operating the standard, 40-W, F-40, T-12, rapid-start, cool-white fluorescent lamps.

Solid-state ballast performance varied widely, from 68 to 79 lumens per watt (lm/W) in efficacy, and from 0.83 to 0.98 in ballast factor. System efficacy was measured at up to 26% higher than standard core-coil ballast efficacy.

Current limiters used with standard core-coil ballasts reduce light output and input power by 30 to 50% and may be suitable as retrofit devices to reduce light in overilluminated spaces. In operation at a constant lamp wall temperature, these devices either maintain or reduce system efficacy.

Dynamic lighting controls (which vary the light output) condition the power to standard core-coil fluorescent ballasts, and low-voltage-type controls alter the oscillating circuit of solid-state ballasts. Power conditioning systems are generally designed to operate many ballasts and most can dim lamps to 50% of full light output. The solid-state ballasts control individual lamps and can dim them to 10% of full light output.

EXECUTIVE SUMMARY

PROJECT DESCRIPTION

Manufacturers are introducing new lighting technologies at a more rapid pace than can be accommodated easily by the usual standards process or evaluation by utility personnel. These technologies—e.g., solid-state ballasts, thermistors for use with incandescent lamps, "no-light" fluorescent tubes, controls to reduce duty cycles, communication over power circuits—are not yet governed by standards or generally accepted specifications. As a result, the products of different manufacturers using the same technology, may vary considerably in performance. Variation in product performance complicates utilities' attempts to recommend new systems and equipment in conservation or peak demand reduction programs because a utility's own research staff must evaluate these new products. Few utilities have the staff or facilities to do this evaluation adequately. In addition, many of these new technologies are based on high-frequency switching techniques that may profoundly influence the electrical supply by distorting current waveshapes and may interfere with communications or computer systems.

PROJECT OBJECTIVES

This study measured and evaluated the performance of auxiliary electric control equipment designed to operate and control gas-discharge lamps. The equipment tested included solid-state fluorescent ballasts; solid-state high-pressure sodium (HPS) ballasts; static controls designed to reduce light from existing lamps; and dynamic controls for varying the light from fluorescent lamps.

PROJECT TASKS

1. Program Plan: Project personnel established a program plan that listed the products to be assessed and submitted a testing plan.

   The equipment tested included at least six types of fluorescent and four types of HID solid-state ballasts; as well as at least four types of static and dynamic controllers.

2. Product Purchase: Researchers procured the equipment in the open market; up to three units of each product depending on cost.

3. Product Testing: Researchers established a set of parameters for each type of equipment to test system efficacy, reliability, and input power conditioning.

4. Three-Phase Model Circuit: Researchers constructed a three-phase experimental model circuit to demonstrate the effects of phase shifts and harmonics on the power source.

5. Data Assessment: The project team prepared a standard form for presenting data and results; including manufacturers' literature.

PROJECT RESULTS

Many manufacturers are introducing auxiliary controls for lighting that vary considerably in performance. Performance differences mean that some equipment is more appropriate for certain applications. End users should be aware of these differences so that they can determine which products best meet their needs.

Solid-State Fluorescent Ballasts

Lawrence Berkeley Laboratory (LBL) tested nine solid-state ballasts operating two or three F-40, T-12, cool-white, rapid-start fluorescent lamps. The initial light output for the same two lamps ranged from 5200 to 6200 lumens (lm) at a 39°C lamp wall temperature to 4800 to 6400 lm at a 50°C lamp wall temperature, which represent typical operating temperatures. The input power for the different systems ranged from 66 to 91 watts (W). They all compare favorably to the standard two-lamp magnetic ballast for the F-40 lamps that provide 6100 lm at 96 W. Solid-state ballast systems increase system efficacy up to 80 lm/W compared with the 63 lm/W for the standard system, which is a 26% increase. Improved solid-state ballast thermal regulation raises system efficacy 35% for some systems at high lamp wall temperature.

Fluorescent lamps operated with some solid-state ballasts have 0% flicker, which makes their use more comfortable for people sensitive to flicker.

Some ballasts remove the filament power during operation, a technique recently introduced by lamp manufacturers. Although these designs may reduce lamp life slightly, they reduce required input power, which may be a cost-effective trade-off.

HID Ballasts

LBL assessed four high-pressure sodium (HPS) solid-state ballasts. Each was designed to operate a different type of HPS lamp, i.e., each had a different power rating. System efficacy is as much as 113% that of standard ballast/lamp systems. However, these ballasts did not improve lamp efficacy as did operation of fluorescent lamps (~15%) at high frequency. One ballast operated the lamp with 60-Hz square wave. In general, the solid-state ballasts are more efficient than HPS core-coil ballasts. Two important features of the solid-state ballast are that they provide the rated power to the lamp over its life, and flicker is virtually eliminated. Standard magnetic ballasts operate the lamps at increasingly higher power levels as the lamps age, which results in energy loss and reduces the lamp life. HPS lamps operated at 60 Hz have 80 to 90% flicker, which is reduced to about 5%, eliminating the possibility of strobascopic effects in industrial applications.

Static Controls

To reduce light in overilluminated spaces, manufacturers have introduced static controls to be used with existing lamps and ballasts. These devices reduce the light output by either 30 or 50%. LBL tested 11 units; 6 were designed for two-lamp F-40, rapid-start systems and 5 for two-lamp F-96, instant-start lamps. At best, the reduction in power is proportional to the reduction in light flux. Two types of units showed a slight gain in efficacy, but this gain resulted from greatly reduced filament power and line-power factor. The static controls that reduced light output by 50% generally lowered system efficacy because of the constant power loss at the filaments. All measurements were made with the lamps at the same lamp wall temperature.

Dynamic Controls

LBL assessed types of dynamic lighting controls that could control fluorescent lamp light output over a continuous range. Four systems were based on conditioning input power to standard ballasts and lamps, i.e., altering either the duty cycle or the supply voltage. The other four devices were solid-state ballasts that controlled the light output by altering the impedance in the oscillating output circuit.

The dynamic controls designed for use with standard ballast/lamp systems are most cost-effective for use with large groups of lamps. These devices have a limited range of control (from 100 to 50% of full light output). The greatest reduction in efficacy is in the range from 100 to 75% of full light output. Below 75% the decrease in light output and power is proportional. Generally, all these systems reduce filament power as the applied power decreases, which may seriously affect lamp life. Solid-state ballasts decrease system efficacy continuously over the entire range of lower light levels. They can dim light down to 10% of full output. All the solid-state ballast systems maintain a reasonable filament voltage over the entire range of light levels. Thus, these systems should provide standard lamp life. However, the cost per ballast controlled is three to four times greater than the cost of controllers that did large banks of lamps. However, the solid-state ballast dimmers are more efficient, dim over a greater range of light levels, can be used for more lighting control strategies, and save more energy. The solid-state ballast system can save more energy by virtue of its greater dimming range and higher efficacy.

Three-Phase Model Circuit

This experiment demonstrated that only the phase shift and the fifth harmonic are reflected to the generating source through three-phase delta-wye-connected transformers. The third, ninth, twelfth, and other harmonics are contained and circulated in the primary transformer. Thus, the greatest problem in operating auxiliary controls in lighting circuits is having the current and voltage in phase. Systems that distort the waveform in lighting circuits generate harmonics that are circulated and dissipate the power in the circuit. This additional power dissipation is a penalty to the end-user.

ACKNOWLEDGEMENTS

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Section 1

INTRODUCTION

During the past several years numerous products designed to reduce the energy consumed by lighting systems have appeared on the market. These products may increase system efficacy, reduce light by a fixed amount, or dim lamps dynamically over a wide range. They affect lamp electrical and photometric properties and influence the supply source. This report presents electrical and illumination measurements of many new products commercially available and supplements current equipment manufacturer information. Measurements were made and analyzed to determine how these products affect lamp performance and power supply. The equipment discussed in this report includes static controls that reduce fluorescent lamp light output and control systems that vary the light output of lamps over a continuous range of light. The project team also measured the performance of solid-state ballasts that operate lamps at high frequency and that can dim lamps over a wide, continuous range. All the equipment was purchased through normal distribution channels. The report has six additional sections: background, a description of parameters measured, test procedures, results of the measurements, a discussion of results, and a summary.

THE READER SHOULD BE AWARE THAT THE UNITS TESTED WERE OBTAINED FROM MANUFACTURERS THROUGH DISTRIBUTORS, RETAIL STORES, OR THE FACTORIES. RESEARCHERS TESTED A VERY SMALL SAMPLE, ONLY THREE UNITS, OF EACH PRODUCT. THROUGH THE TEST RESULTS MAY REFLECT GENERAL TRENDS, THE MEASURED VALUES PRESENTED IN THIS REPORT MAY NOT REPRESENT MEAN VALUES. IN ADDITION, PERFORMANCE MAY CHANGE BECAUSE SOME PRODUCTS WERE TESTED IN THEIR EARLIEST STAGES OF COMMERCIALIZATION, AND THEIR COUNTERPARTS NOW ON THE MARKET MAY HAVE BEEN CHANGED BY THE MANUFACTURER.

Section 2
BACKGROUND

Electric lighting represents more than 20%[1] of total national electric energy consumption (450 billion kWh annually)[2] and is an important concern for utilities and users alike. The widespread use of power-reducing and energy-efficient lighting systems may slow the rate at which energy consumption is increasing. Reduced lighting load may help utilities because lighting is used primarily during peak demand hours. Reduced peak demand will smooth utility load profiles, lessen the need for expensive peak-load generating equipment, and reduce the need for new generating capacity.

If utilities are to make well-informed recommendations to their customers on these products, they must understand how much energy can be saved and how these devices are best used. The energy-saving lighting controls described in this report save significant energy while maintaining and, in some cases, improving illumination quality. Savings estimates range from 20% to nearly 70%. However, because these products are new technologies, they are not subject to standards that regulate established product performance. One can reduce power by lowering light output or by improving a ballast's efficiency. Manufacturers of the new devices may select ways of reducing power that differ from the American National Standards Institute (ANSI) standards for similar systems.[3] Different versions of a product may work in different applications, and utilities must be aware of these differences to foster appropriate use. Product literature emphasizes a new product's advantages. This report objectively treats product performance differences and discusses their impacts.

The new lighting equipment uses different circuit concepts to operate and control gas-discharge lamps, e.g., switching power supplies or controlling the duty cycle of the input. These techniques affect the electric supply by altering the phase relationship of the current and voltage and by creating non-sinusoidal waveshapes. This change generates higher-frequency signals on the power lines, which are harmonics of the input and output frequencies. Although these new systems comprise only a small proportion of lighting installations, they may be widely used in the future, and thus utilities must be aware of their potential effect on the power supply system.

Section 3

PERFORMANCE PARAMETERS

Lawrence Berkeley Laboratory (LBL) designed and performed a series of tests to study the following parameters.

SYSTEM/COMPONENT EFFICACY

Efficacy is the term used to describe how effectively a system or component converts electric energy into visible light. Measuring input power to the ballast and lamp and light output from the lamp determines efficacy. The term, which is applied to the whole system and to lamps, is expressed as dimensional units of measure—for example, as lumens/watt (lm/W). Efficiency, which describes ballast performance, is used for a nondimensional quantity.

The lamp efficacy is a function of minimum lamp wall temperature (MLWT). LBL tested the lighting devices at 40 and 50°C lamp wall temperatures, which represent the end points of the typical operating range for fluorescent lamps in most fixtures. The test data obtained permit assessment of ballast efficiency and system/lamp efficacy.

$$\text{Ballast efficiency} = \frac{P_{in} - P_{out}}{P_{in} \text{ to ballast(W)}} \times 100 \tag{3-1}$$

$$\text{Lamp efficacy} = \frac{\text{Light out (lm)}}{P_{out} \text{ to lamp (W)}} \tag{3-2}$$

$$\text{System efficacy} = \frac{\text{Light out (lm)}}{P_{in} \text{ to ballast (W)}} \ , \tag{3-3}$$

where P_{in} is the input power to the ballast or lamp as indicated, P_{out} is the ballast output power (input power to the lamps). Light out is the total system/lamp light output. System efficacy is the key parameter for determining a system's operating costs because it describes the power needed for illumination.

INPUT/LAMP WAVESHAPES

Obtaining the waveshapes to the lamp enables calculation of the current crest factor: I(peak) ÷ I(rms). ANSI specifications require that lamps be operated with a crest factor equal to or less than 1.7; a sine wave has a crest factor of 1.4. Operating lamps with higher crest factors tends to reduce lamp life. However, no information is available to determine whether this crest factor limit applies to lamps operated at higher frequencies.

Determining the waveshape to the ballast (supply waveshape) enables a rapid estimation of input voltage and current distortion (from the sinusoidal). One can readily observe whether this nonsinusoidal shape and/or the phase relationship between the current and voltage will reduce the power factor. In addition, one can determine the existence of high-frequency harmonics. Further quantitative measurements of these parameters are described below.

HARMONIC CONTENT

Nonsinusoidal waveshapes generate higher harmonics of the fundamental 60-Hz line frequency. The neutral line for a pure sinusoidal current, in a balanced three-phase circuit carries no current, i.e., the fundamental of each phase is 120° out of phase, so the phases cancel each other in the return line (neutral). However, a third harmonic will cause current to flow in the neutral line. If the third harmonic is large, the neutral line can become overloaded. Harmonics can also interfere with other electrical appliances on the circuit.

CONDUCTED ELECTROMAGNETIC ENERGY

Solid-state ballasts convert the 60-Hz input power to direct current and invert this current to a high frequency (generally between 20 and 30 kHz) and supply it to the lamp. The high-frequency power fundamental and its higher harmonics are reflected back into the supply power. This reflected power can interfere with other appliances on the line, and supply lines can radiate it into space, where it can interfere with space-radiated communications. The Federal Communications Commission (FCC) is concerned with this potential source of interference and has been working with a subcommittee of the National Electrical Manufacturers Association (NEMA) to establish guidelines for controlling it. LBL is also working in this area; in two on-site demonstrations LBL measured the radiation levels and noted no interference problems. No occupants reported adverse effects on office or communication equipment.[4,5]

NEAR-FIELD RADIATED ELECTROMAGNETIC ENERGY

Lamps operated with high-frequency solid-state ballasts emit electromagnetic (EM) energy of fundamental and higher harmonic frequencies. Because fluorescent lamps are only 4 ft long, they are not efficient antennae at kHz frequencies. Through capacitive coupling in the near field, they could interfere with other electric appliances. The FCC, NEMA, and LBL are investigating these effects. LBL has measured these fields in various demonstrations and found no adverse effects where fluorescent lamps had been used.[4,5] However, the EM radiation from high-frequency fluorescent lamp systems radiate greater EM energy intensities than do 60-Hz systems.

FLICKER

The percent flicker is a measure of the modulation of the light output and is defined as the difference between the maximum and minimum intensity divided by their sum. Fluorescent lamps operated on 60-Hz electrical systems flicker at a rate of 120 Hz and have a 33% flicker. Solid-state ballasts operate lamps at 20 kHz and, when unmodulated, reduce flicker to 0%. However, some ballasts modulate the high-frequency power to the lamp at 60 Hz. Depending on the modulation scheme, the percent flicker can vary between 0 and 33%. When they design particular circuits, some manufacturers may choose between improving the power factor and increasing the modulation (i.e., the percent flicker).

Flicker can cause discomfort and reduce productivity. Typically it affects only a small portion of the population. Some evidence shows that lamp flicker will affect more people who work with video displays because it may interact with display refresher rate.[6] Reducing flicker is one important advantage of operating fluorescent lamps and high-intensity discharge lamps at high frequencies.

LIGHT OUTPUT

Input power alone cannot measure ballast energy performance. The ballast factor at which the lamp operates is another important measure because it describes the relationship of the lamp's actual light output to the manufacturer's rated light output. Core-coil ballasts that meet the ANSI standards give minimum light based on the lamp's rated output. For example, ballasts approved by the Certified Ballast Manufacturers Association (CBM) have a ballast factor of at least 95 ± 2 1/2% of the manufacturer's rated output for a standard F 40, rapid-start, argon-filled lamp. No ANSI standards currently exist for other 4-ft lamps, such as the energy-saving 35- and 34-W lamps.

Ballast factors are significant only because their values determine the applications for which a ballast is most appropriate. In renovations and new construction a high ballast factor may be more economical because fewer fixtures, lamps, and ballasts would be necessary to provide a specific illumination level.[7] Low-ballast-factor ballasts can be used to retrofit spaces that are over-illuminated.

A particular ballast factor depends on lamp type as well as minimum lamp wall temperature. For example, the CBM core-coil ballast has a ballast factor of 95 ± 2 1/2% for F 40, T-12, rapid-start, argon-filled lamps when tested in a room ambient temperature of 77°F. The same ballast will have a ballast factor of about 87% when used with a 34-W, T-12 rapid-start, krypton-filled lamp. At increased lamp wall temperatures, the ballast factor for core-coil ballasts will decrease. The ballast factors for solid-state ballasts are less sensitive to changes in lamp wall temperature.[7]

REGULATION

Ballasts are designed to operate over a voltage range of ± 10% about the center design voltage.[3] Variation in light output as a function of change in input voltage defines regulation. In general, the minimum light output occurs at the minimum input voltage, i.e., at 10% below the center design voltage. Lighting layout design must account for the input voltage range so that effective lighting is available even at input voltages 10% below the center design voltage. Highly regulated ballasts provide constant light levels over the ± 10% range of input voltages. Loosely regulated systems require higher average light levels to compensate for conditions when the input voltage is below the center design voltage. However, if the line voltage is controlled, loosely regulated ballasts can be used as dimming ballasts.

STARTING CHARACTERISTICS

The ANSI specifies the maximum starting voltage for F-40 lamps.[3] The life of rapid-start lamps started at voltages above this maximum (360 V) will be reduced. High starting voltage increases ion acceleration and causes the ions to strike the filament too forcefully, which removes its excessive low work function coating.

The open-circuit voltage is a measure of maximum voltage that can be applied to the lamps at starting. Good ballast designs have heated filaments and limit the magnitude of the open-circuit voltage to less than the ANSI standard.

POWER FACTOR

The phase relationship between the voltage and current and the nonsinusoidal waveshape determines the line power factor. ANSI specifies that a "high-power-factor ballast" must have a power factor equal to or greater than 90%. This power factor is achieved in a core-coil ballast by a suitably sized capacitor, which decreases the voltage-current phase angle.

The nonsinusoidal waveshapes produced by solid-state ballast systems also reduce line power factor. Utilities' primary concern in three-phase circuits is the out-of-phase current-voltage relationship, because it is reflected back to the generation source. The "shape" power factor causes a higher volt-ampere (VA) to circulate within the circuit, which increases the line losses and requires a larger wire size but does not influence the generation source.

FILAMENT POWER

The heated electrodes (filaments or cathodes) of a rapid-start fluorescent lamp permit the lamp to be started at a lower voltage by increasing the thermionic emission. The tungsten filaments are immersed in alkali earth material to reduce the work function. For this reason rapid-start lamps have a longer life, and their ends do not blacken as severely as instant-start or preheat-start fluorescent lamps. ANSI specifies that 2.5 to 4.1 V be continuously supplied to these electrodes.

Some solid-state ballasts as well as some new core-coil ballast and fluorescent lamps reduce or eliminate the filament voltage after starting. The manufacturers of lamps and these new core ballasts also have designed a sturdier lamp filament to be used with the ballast. This lamp's lifetime has been rated at 15,000 h.

Removing all filament power on a two-lamp system will save about 4 W; however, the savings is obtained at the expense of lamp life. This phenomenon applies when the lamp is operated at full light output. When a lamp is dimmed, removing filament power greatly reduces lamp life. Researchers at LBL have observed lamp lives of only 100 to 200 h when lamps are operated at 30% of full light output without any filament power.

Section 4

EXPERIMENTAL PROCEDURE

LAMP LIGHT FLUX OUTPUT

One important parameter of lighting systems is the total light flux from the lamp-ballast systems. Because measurements were made on the same fluorescent lamps over several months, they were burned in about 1000 hours to reduce the lamp lumen depreciation rate. This procedure reduced the light output to well below manufacturers' rated initial output. The rated initial output for F-40, T-12, rapid-start, cool-white lamps is 3150 lm. To obtain the lamps' absolute light output and convert it to initial output required several calibration constants: the sphere photometric parameter, the fixture geometric constant, the sphere lamp test fixture constant, and the initial light flux parameter.

Sphere: Photometric Parameter

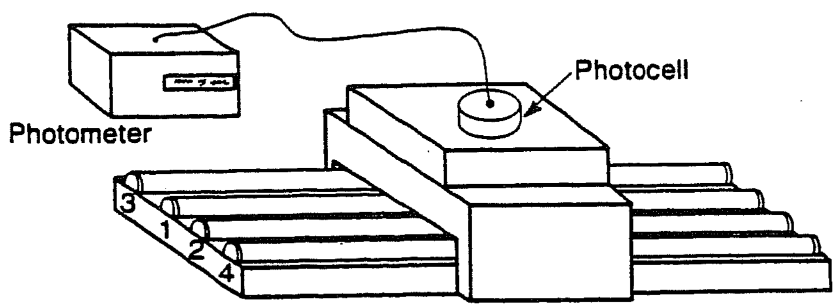
The Tektronix J-16 photometer measures illumination in units of lux (lumens per square meter), which is proportional to the total light flux (lumens) from the light source. Standard calibrated fluorescent lamps, producing known light flux, are used to calibrate the sphere and convert the photocell output (lux) to light flux (lumens). Dirt accumulation requires that the sphere be recalibrated periodically. The sphere was calibrated twice during these experiments. The sphere-photometer parameter (SP) was found to be 1.193 and 1.210 lumens per lux lm/lx. The average value is 1.201 ± 1% lm/lx.

Fixture: Geometric Constant

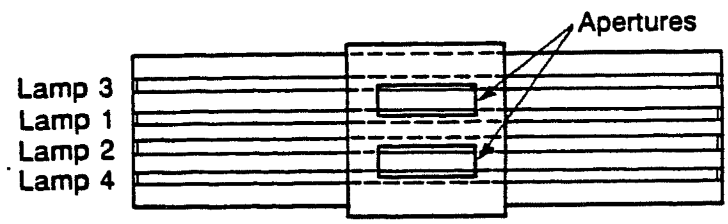
Figure 4-1 is a schematic drawing of the lamp test fixture designed for this study. The fixture can test one to four fluorescent lamps. Not shown are the electrical connections and thermocouples that measure the input electrical characteristics and the minimum lamp wall temperature, respectively. The photocell, which senses light output, measures only a portion of the output from each lamp. In this test, researchers measure a standard lamp in the integrating sphere and in the lamp test fixture and, using the latter measurements determine the total flux from each lamp:

$$\text{Total light flux}_{(\text{sphere})} = K \times \text{fixture measurement} \tag{4-1}$$

where K is a constant that relates the two measurements.



(a) Lamps and Chamber



(b) Aperture Between Lamps and Photocell

Figure 4-1. Lamp Test Fixture

However, K has a different value for each lamp position. If K is unique for each position, two measurements are required for a two-lamp system, three measurements for a three-lamp system, and so on, to determine each K value. To reduce the number of measurements, researchers designed a two-aperture structure to experimentally render the geometric factor the same for all positions (Figure 4-1b). Table 4-1 shows the change in the fixture geometric factor for a single and double aperture. The average value of the geometric factor is 1.001 ± 0.006, ± 0.6% for the double aperture. Thus, K is independent of lamp position and has the same value for one, two, three, or four lamp measurements.

<u>Sphere: Lamp Test Fixture Constant</u>

Standard calibrated fluorescent lamps were used to determine the sphere-lamp test fixture constant (K_n). This constant relates the light measurements made in the lamp test fixture to the total light flux of that lamp as measured in the integrating sphere. The experiment measured six calibrated fluorescent lamps in a standard

Table 4-1

FIXTURE GEOMETRIC FACTOR

Position	Aperture	
	Single	Double
1	0.600	0.994
2	0.612	1.006
3	0.143	1.008
4	0.139	0.996

environment (25°C, 77°F) in the integrating sphere with a reference ballast set at a 439-ohm impedance and a 236 V. input voltage. This experiment measures the absolute value of each lamp's total light output (lm). The lamps are then measured under identical conditions in the test fixture, and a light meter reading, which is proportional to the total light flux (lx), is recorded. From these data the sphere-lamp test fixture constant K_n (lm/lx) can be determined. Table 4-2 lists the results of the measurements for each standard lamp measured in the sphere and the four positions in the lamp test fixture.

Initial Lamp Light Flux

To slow the rate of lamp lumen depreciation, researchers burned-in the F-40, T-12, rapid-start, cool-white lamps used to measure the performance of the ballast and controls for more than 1000 hours before any tests. This ensured that the lamps' light output would change very little during testing. However, lighting system performance (lamp and system efficacy) is generally expressed in terms of a lamp's initial light output under standard ANSI conditions. To compare results with existing published data, LBL personnel normalized the measured light output data to their initial light output.

Each set of measurements includes the measured lamp light output with either a CBM 120-V General Electric, or a CBM 277-V Universal Manufacturing Co. ballast. These ballasts are secondary references. Their ballast factors have been compared with a reference ballast. That is, the change in light output of the lamps operated with

Table 4-2

SPHERE LAMP TEST FIXTURE CONSTANT

Lamp (F-40,T-12)	Lamp Operation: Voltage (V)	Current (A)	Power (W)	Light Meter Reading: Sphere (lm)	Fixture (lx)	Fixture[a] Constant (lm/lx)
A-1	81.3	0.458	32.8	2980	592	5.03
A-2	81.7	0.457	33.0	2930	581	5.04
A-3	81.9	0.456	33.0	2950	584	5.04
B-1	99.1	0.432	38.3	3070	614	5.01
B-2	99.3	0.433	38.1	3070	609	5.04
B-3	99.4	0.431	38.3	3010	603	5.01

[a]The sphere-lamp test fixture constant (Kn) is 5.030 ± 0.2% lm/lx.

the CBM ballast was compared with the light output of the lamps operated with the reference ballast, measured under ANSI conditions. The ballast factors are 0.968 and 0.949 for the 120- and 277-V ballasts, respectively. The rated initial light output of a single F-40, cool-white lamp is 3150 lm; thus, the adjusted rated initial light outputs of the lamps with the two CBM ballasts are 3050 and 2990 lm, respectively. The measured lamps will put out less light because they were burned-in for more than 1000 h. The initial light output of the test lamps is 3050 lm, or 2990 lm divided by the light output of the 120- or 277-V ballasts, respectively.

These calibrations permit determination of the absolute light output from the tested systems and relate the measurements to the initial lamp output. All these calibrations are accurate to less than ±1%, less than the instrumented errors of ± 5% absolute and ± 2% relative.

FLUORESCENT BALLASTS

Test Circuit

Figure 4-2 is a schematic of the test circuit used to measure fluorescent lamp system performance. The system permits researchers to test a standard core-coil CBM ballast first and then measure the solid-state test ballast. The core-coil ballast establishes baseline data for the lamp's performance (secondary ballast standard). As discussed in the previous section, the lamp's initial light output can be calculated to determine the system's initial performance.

Open-Circuit Voltage

LBL measured the ballasts' open-circuit performance to determine the electrical conditions under which the lamps are started. At 90, 100, and 110% of the rated input voltage, they measured the root mean square (rms) open-circuit lamp voltage (V_{oc}) and the peak open-circuit lamp voltage (V_{ocp}).

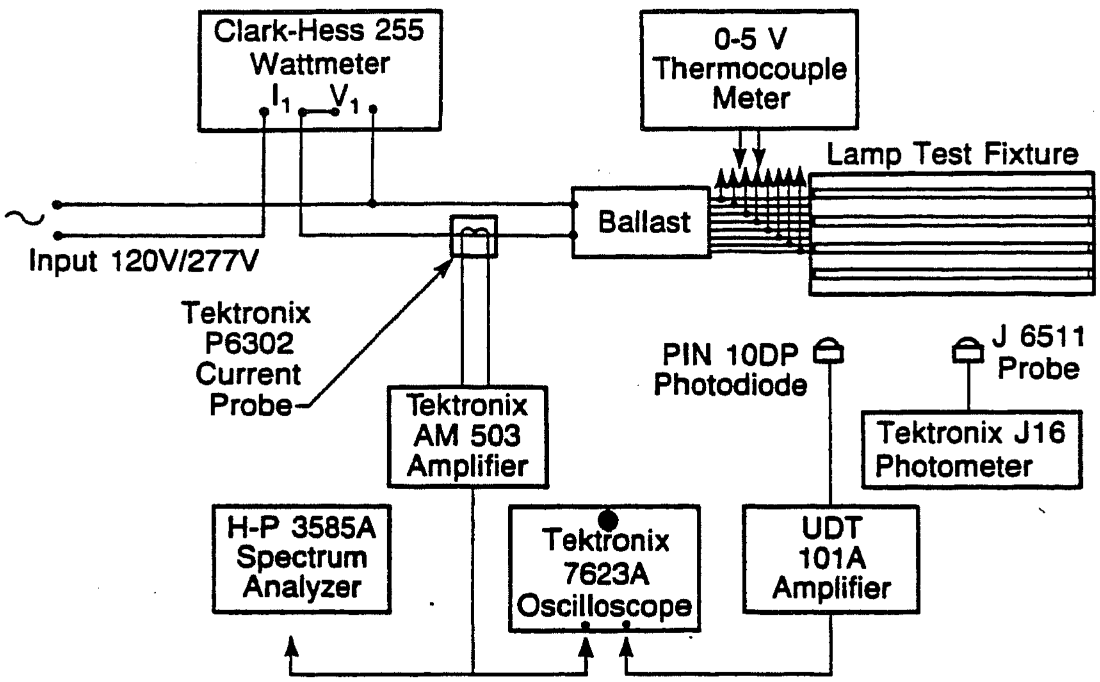


Figure 4-2. Fluorescent Lamp Ballast Test Circuit

System Performance

The lamps were inserted into the test fixture and operated for 15 minutes to obtain thermal equilibrium. Researchers measured the lamp wall temperature; in the two-lamp system the optimum, 40°C, was achieved at 25°C ambient temperature. The following parameters were then measured at 90, 100, and 110% of the rated input voltage: line voltage, V_{in} (V); line current, I_{in} (A); input power, P_{in} (W); filament voltage, V_{kl} (V), where l = 1, 2, 3, or 4 (the number of filaments); and light output, = Φ_L (lx). (Using the appropriate conversion factors, the light output, lx, can be converted to absolute total flux, lm, and to initial light output, lm.)

At the center voltage, the line harmonics were measured (fundamental, second, third, fourth, fifth, seventh, and ninth) with a Hewlett-Packard Spectrum Analyser. The data are presented as percentages of the fundamental harmonics.

Oscilloscope photographs were obtained of the input voltage and current waveforms as well as the voltage and current waveforms to the lamp. The latter traces permit determination of the current crest factor. Light modulation (flicker) was also determined by measuring the light output with a photodiode and displaying the output of the photodiode amplifier on the oscilloscope. Researchers again measured system performance at a lamp wall temperature of 50°C at the rated line voltage.

Dimmable ballast systems were measured at the rated line voltage at full, mid, and minimum light output. The minimum light output—the lowest level to which lamps can be dimmed without any evidence of light striations or lamp instabilities—is determined experimentally.

Calculation of Performance Parameters

Researchers calculated several performance parameters from the following relationships.

Absolute light output (Φ):

$$\Phi \equiv Kn\ (lm/lx) \times \Phi_L (lx)$$

Initial light output (Φ_i):

$$(\Phi_i) = \frac{3150 \times \text{Ballast factor (core)}}{\Phi_{core}} \times \Phi_{solid\text{-}state}\ (lm)$$

Initial system efficacy (E_i):

$$E_i = \Phi_i / P_{in}\ (lm/W)$$

Percent flicker (f):

$$f = \frac{\text{Peak intensity} - \text{Minimum intensity}}{\text{Peak intensity} + \text{Minimum intensity}} \times 100$$

Voltage-light output regulation (R_v)

$$R_v = \frac{\Phi \text{ at } 90\%\ V_{in} - \Phi \text{ at } 100\%\ V_{in}}{\Phi \text{ at } 100\%\ V_{in}}$$

and

$$= \frac{\Phi \text{ at } 110\% \text{ and } V_{in} - \Phi \text{ at } 100\% \ V_{in}}{\Phi \text{ at } 100\% \ V_{in}}$$

Power factor (PF)

$$PF = \frac{P_{in}}{V_{in(rms)} \times I_{in(rms)}}$$

Filament power (P_f):

$$P_f = \frac{V_k^2}{R_k} \ (R_k = \text{filament resistance})$$

Open-circuit crest factor (CF_{oc}):

$$CF_{oc} = V_{ocp}/V_{oc(rms)}$$

Lamp current crest factor (CF_l):

$$CF_l = I_l \text{ peak}/I_{l(rms)}$$

Thermal/light output regulation (R_T):

$$R_T = \frac{\Phi \ 40°C - \Phi \ 50°C}{\Phi \ T \ °C}$$

HIGH-PRESSURE SODIUM VAPOR BALLAST

Figure 4-3 is a schematic of the test circuit for evaluating high-pressure sodium vapor (HPS) lamp systems. Researchers measured systems with the lamps in the integrating sphere. Thus, they had to use only the sphere-photometric parameter to convert the measured light (lx) to total light flux (lm). Each system's performance is compared with that of lamps operated with a conventional core-coil ballast.

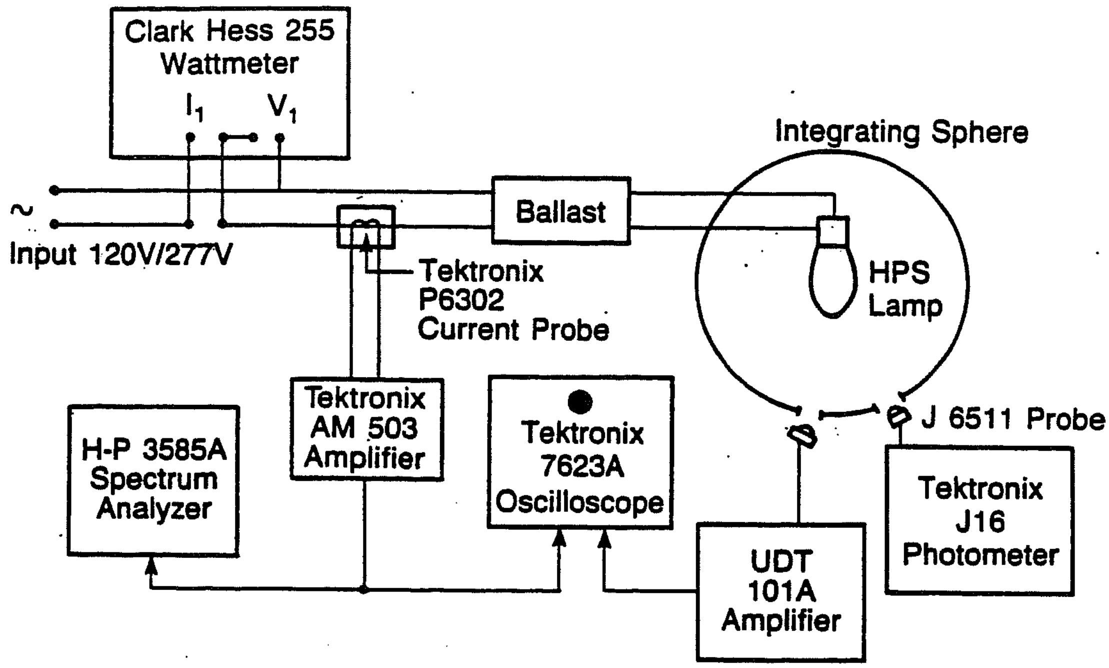


Figure 4-3. High-Pressure Sodium Ballast Test Circuit

Open-Circuit Voltage

Researchers measured the ballast open-circuit output at 90, 100, and 110% of the rated input voltage. HPS lamp systems have a special circuit that starts the discharge with a suitable voltage spike of several kV. Therefore in the open circuit the system activates the starting circuit and the high-voltage spike can be measured. Once the HPS lamp is ignited, the starting circuit is bypassed. LBL photographed an oscilloscope trace of the pulse.

System Performance

Researchers measured the following parameters at 90, 100, and 110% of the rated output voltage: line voltage, V_{in}, (V); line current I_{in} (A); input power P_{in},(W); light output Φ_L(lux). (This measure was converted into total light flux, lm, by the sphere-photometric parameter, lm/lx.)

LBL phtographed the line and lamp current waveforms to determine crest factor. Project personnel measured the line harmonics (fundamental, second, third, fifth, seventh, and ninth); they also measured the light output modulation by connecting the photodiode amplifier output to the oscilloscope and recording maximum and minimum values of light output.

Calculation of Performance Parameters

Absolute light output (Φ):

$$\Phi = Kn \times \Phi_L \text{ (lx)} \times \text{Sphere-photometer parameter (lm/lx)}$$

Initial system efficacy (E_i):

$$E_i = \Phi_i / P_{in} \quad \text{(lm/W)}$$

Percent flicker (f):

$$f = \frac{\text{Peak intensity} - \text{Minimum intensity}}{\text{Peak intensity} + \text{Minimum intensity}} \times 100$$

Voltage-light output regulation (R_v):

$$R_v = \frac{\Phi \text{ at } 90\%\ V_{in} - \Phi \text{ at } 100\%\ V_{in}}{\Phi \text{ at } 100\%\ V_{in}}$$

and

$$= \frac{\Phi \text{ at } 110\%\ V_{in} - \Phi \text{ at } 100\%\ V_{in}}{\Phi \text{ at } 100\%\ V_{in}}$$

Power factor (PF):

$$PF = \frac{P_{in}}{V_{in(rms)} \times i_{in(rms)}}$$

CONTROLLERS

Lighting controllers are systems that dim fluorescent lamps. Two types are the solid-state ballast systems that provide this feature as an inherent characteristic and devices designed to control a standard core-coil ballast. All systems were tested for performance with a single two-lamp F-40, F-12, rapid-start, core-coil ballasts; testing the 16A and 20A systems fully loaded was not practical.

Dimmable Ballasts

Dimmable ballasts are special solid-state ballasts; the same procedure is used to measure their performance as described in the solid-state ballast section.

Ballast Input Controllers

Figure 4-4 is a schematic of the test circuit for assessing the performance of add-on controllers. LBL used the lamp test fixture because researchers were interested in relative changes in efficacy and light output.

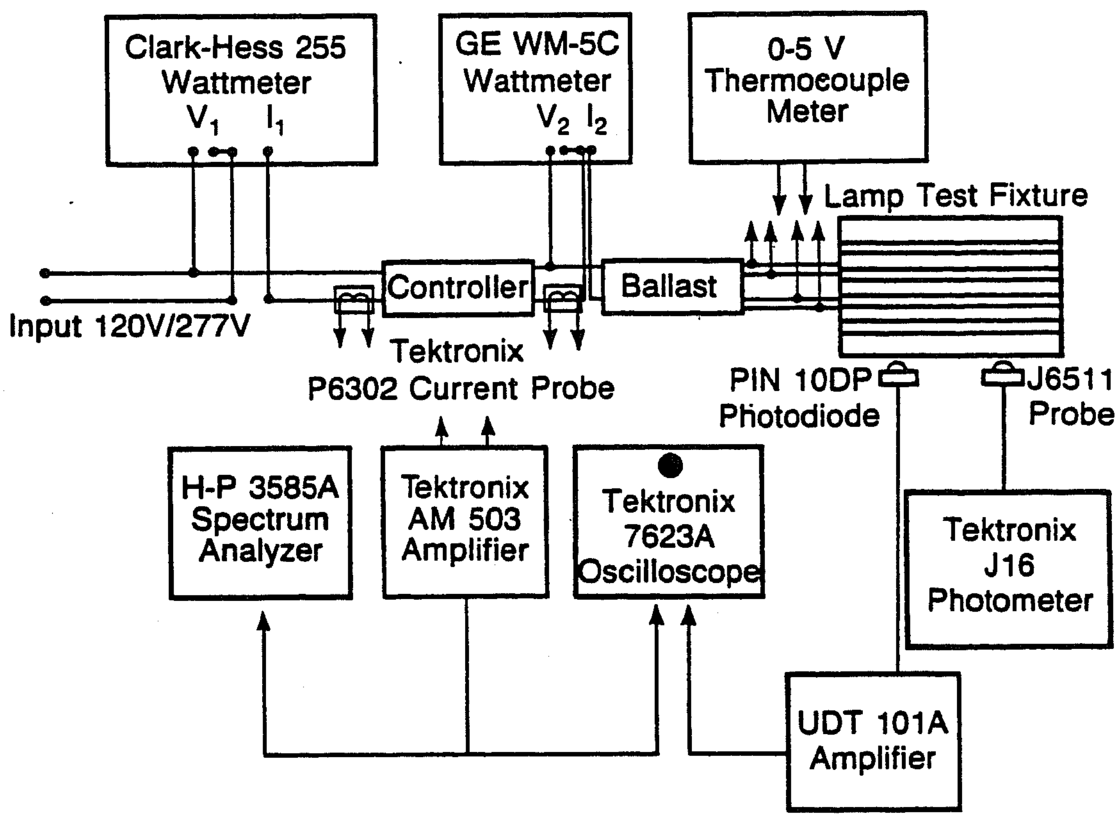


Figure 4-4. Test Circuit for Add-on Controllers

For the baseline, the ballast lamp system is measured at the rated line voltage with the controller out of the circuit. Researchers recorded line voltage, V_{in} (V); line current, I_{in} (A); input power, P_{in} (W); filament voltage, V_{kl} (V) $l = 1, 2, 3$; a function of lamps); light output, Φ_L (lx); harmonic content, I_{k1} (fundamental, second, third, fifth, seventh, and ninth); and lamp wall temperature, T_L (°C). They photographed line and lamp current waveshapes as well as light modulation, and measured maximum and minimum values of wave traces.

Some controllers are placed in front of the ballast; others are connected between the ballast and the lamp. In these tests the controller was placed into the circuit as specified by the manufacturer. Researchers measured the parameters listed above at maximum, minimum, and mid light output. Minimum light output is that at which the lamp still operates normally without any striations or other disturbance. The midpoint is halfway between maximum and minimum output.

Calculation of Performance Parameters

Light output, Φ:

$$\Phi = Kn \times \Phi_L \text{ (lx)} \times \text{Sphere-photometric parameter (lm/lx)}$$

Percent flicker (f):

$$f = \frac{\text{Peak intensity} - \text{Minimum intensity}}{\text{Peak intensity} + \text{Minimum intensity}} \times 100$$

System power factor (PF):

$$PF = \frac{P_{in}}{V_{in(rms)} \times I_{in(rms)}}$$

Filament power (P_f):

$$P_f = \frac{V_k^2}{R_k}$$

Light output plot of Φ vs P_{in}.

STATIC CONTROLS

Description

These systems dim fluorescent lamps to one predetermined light output. Devices are designed to reduce the light levels by either 30% or 50%, and are for use with only conventional core-coil ballasts.

LBL measured a conventional core-coil ballast fluorescent lamp system to establish the baseline. Then researchers connected the static controller to the circuit as described by the manufacturer. Figure 4-5 is a schematic of the test circuit. The measured parameters include line voltage, V_{in} (V); line current, I_{in} (A); system power, P_{in} (W); light output, Φ_L (lx); harmonics (fundamental, second, third, fifth, seventh, and ninth); lamp wall temperature, T_L (°C); and filament voltage, (V_{k1} - V_{k3}).

Researchers recorded oscilloscope photographs of the current waveforms, input to the system, input to the ballast, and input to the lamps, as well as measured photodiode output to record light modulation.

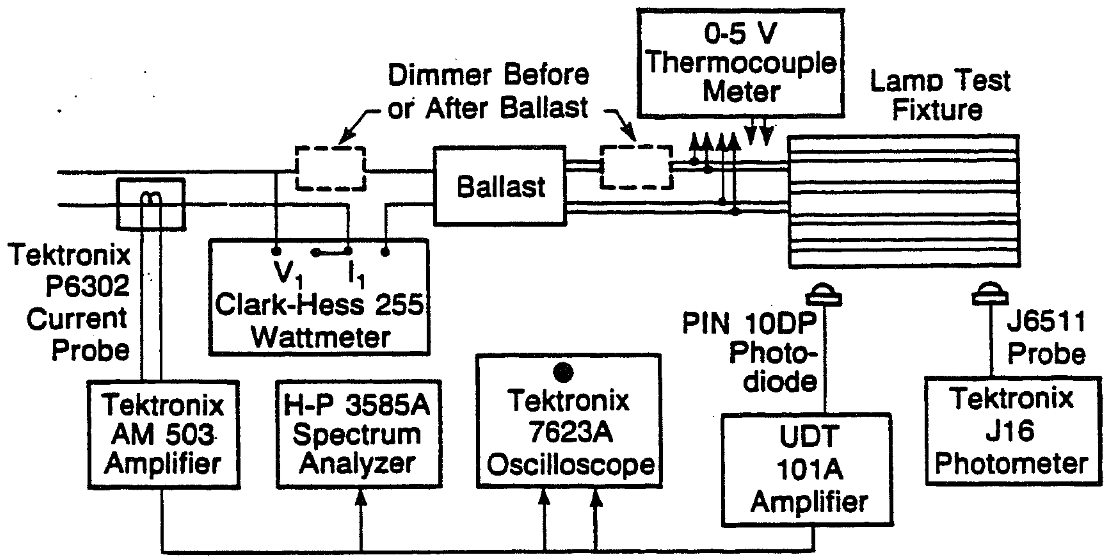


Figure 4-5. Static Controller Test Circuit

Calculation of Performance Parameters

Light output:

$$\Phi = Kn \times \Phi_L(lx) \times \text{Sphere photometric parameter (lm/lx)}$$

Percent flicker (f):

$$f = \frac{\text{Peak intensity} - \text{Minimum intensity}}{\text{Peak intensity} + \text{Minimum intensity}} \times 100$$

System power factor (PF):

$$PF = \frac{P_{in}}{V_{in(rms)} \times I_{in(rms)}}$$

Filament power (P_f):

$$P_f = \frac{V_k^2}{R_k)}$$

ELECTROMAGNETIC MEASUREMENTS

No standard procedures exist for measuring the electromagnetic interference (EMI) from a lighting system. The recent introduction of high-frequency lighting systems has created concern about, conducted and radiated EMI. Installations of high-frequency solid-state ballasts have not affected office or hospital operations.[4,5] LBL is conducting research in this area to develop criteria for establishing acceptable EMI limits.[13] The lighting industry is concerned with near-field EMI radiation. Research in this area measures broad band noise to determine solid-state ballast EMI compared with that emitted by standard core-coil ballast systems.

Radiated EMI

Figure 4-6 is a schematic of the experimental arrangement for measuring radiated EMI. The two-lamp ballast system is in a bare lamp fixture. An AH-system SAS 200/550 active monopole antenna is placed 1 m from the lamp/ballast system. This distance is measured from the center of the antenna. A Hewlett-Packard spectrum analyzer 3585A measures the electric field and the fundamental peak at 20 kHz.

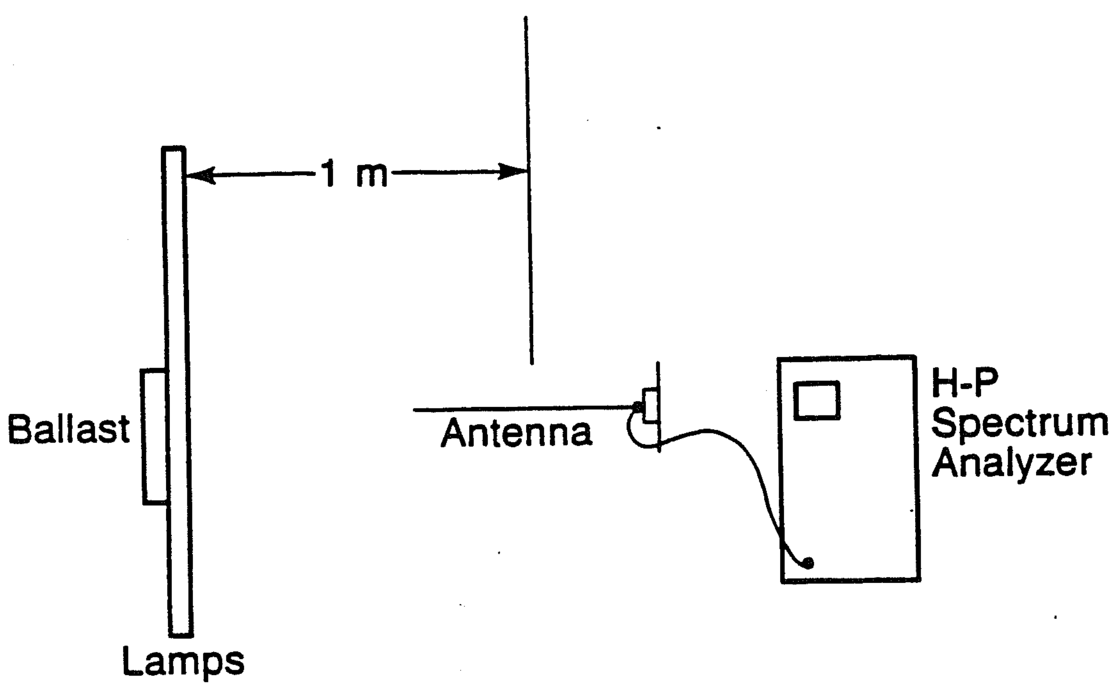


Figure 4-6. Test Arrangement for Radiated EMI Measurement

The analyzer can display the EMI signature field as a function of frequency. However, the broad-band measurement gives total emissions over a wide band of frequencies and a simple figure of merit for comparing various systems. Researchers also measured the EMI radiated field with a Hewlett-Packard rms voltmeter, which responds from 10 Hz to 10 mHz. Both methods require correction by an antenna factor. The measured field is expressed in terms of dBμV/m.

Conducted EMI

Conducted EMI is the electromagnetic energy emitted by a ballast through its power system. The conducted energy may present a greater problem than radiated EMI because the distribution system is a more efficient radiator than the 4-ft lamps at 20 kHz. In commercial buildings metal conduits normally housing the wiring will lessen this problem. If conducted EMI is too great, the metal conduits can be grounded to shield the conducting cables. Conducted EMI may pose a greater problem in residences, however, where distribution wiring usually is not contained in metallic conduits.

Figure 4-7 shows the experimental arrangement for measuring conducted EMI. Researchers measured EMI with the Hewlett-Packard spectrum analyzer current probe attached around the power cable hot lead. The EMI signal load for measuring conducted emissions must be specified, and the 10-μF capacitor is used as a standard. The capacitor represents a low-impedance load (therefore maximum current flows through the capacitor), which is detected by the current probe.

The current probe, shown in Figure 4-8, is a transformer with the tested power line as the primary winding and core winding as the secondary.

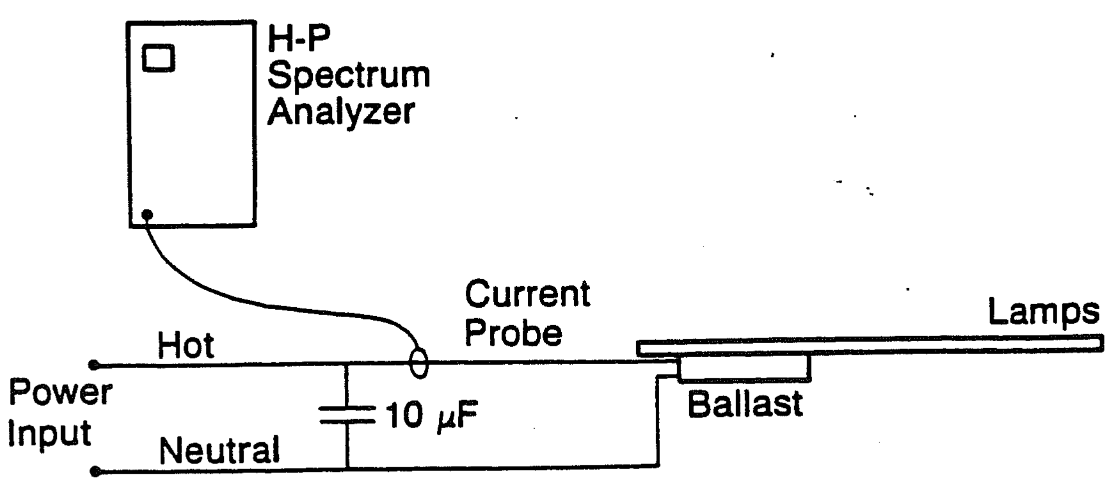


Figure 4-7. Test Arrangement for Conducted EMI Measurement

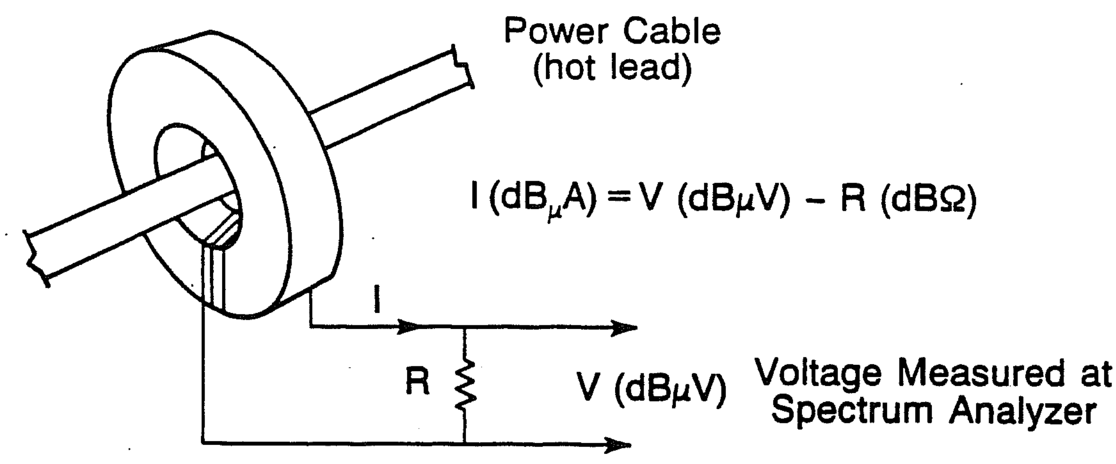


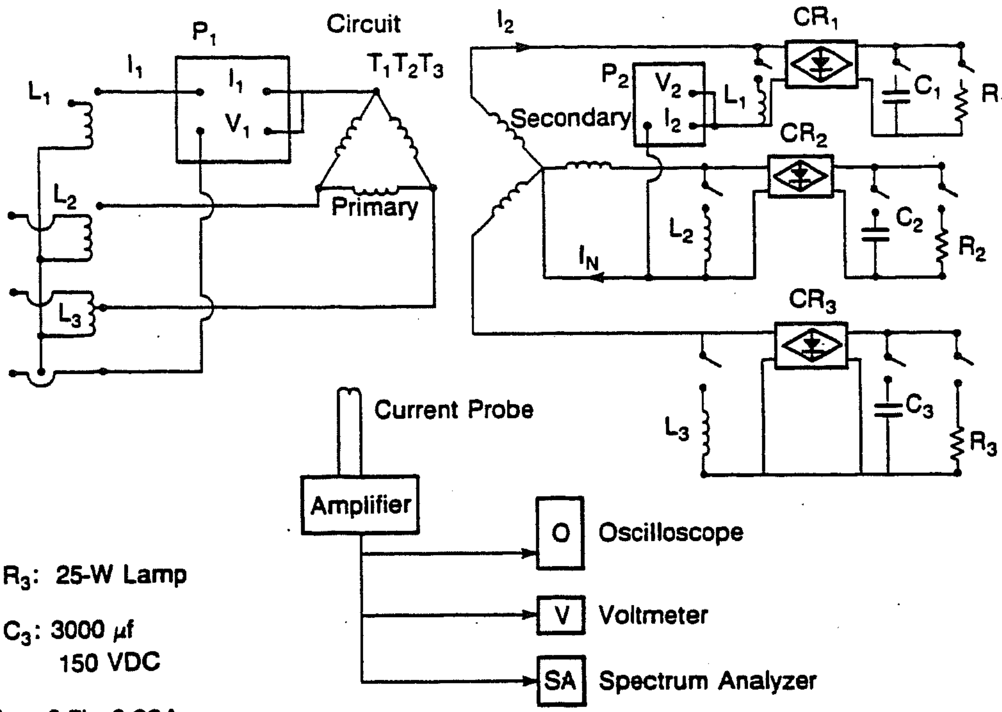
Figure 4-8. Current Probe Transfer Function

A transfer function converts output voltage measured by the spectrum analyzer to the current flowing in the power line. The transfer function (in dBΩ) is subtracted from the voltage (dbμV) to obtain the conducted EMI in terms of current (dBμA).

THREE-PHASE DELTA-WYE CIRCUITS

Figure 4-9 shows a schematic of the circuit used to measure the effects of current-voltage phase shifts and line harmonics on the primary and secondary of a three-phase delta-wye connected system. Inductors, capacitors, and resistors produced phase shifts and harmonics in the three secondary circuits. Researchers made all measurements with the secondary circuits balanced, and measured the current in the secondary legs and neutral. They also measured the current and power in the primary and determined the power factor in the primary and secondary from the standard relationship of rms current, rms voltage, and measured power. Researchers measured the third and fifth harmonics using the Hewlett Packard spectrum analyzer in the secondary and primary circuits. They made five sets of measurements, simulating a resistive circuit, pure inductive circuit, saturated inductive circuit (which provides some harmonics), a pure harmonic content, and an inductive-harmonic content. They measured the circuit parameters in each of the lamp branches and then measured the circuits with 80 V across the inductors L_1, L_2, and L_3. The voltages in the secondary were increased by adjusting the Variac V_{a1}, V_{a2}, V_{a3} in the primary. The inductor, when saturated, generates a small number of harmonics.

The purpose of these experiments was to demonstrate the effects of the shapes and phase relationships of the voltage and current. A balanced three-phase circuit is used to make certain the currents measured in the neutral are only due to the wave distortions and phase relationships of the reactive components of the loads.



Legend

R_1, R_2, R_3: 25-W Lamp

C_1, C_2, C_3: 3000 μf
150 VDC

L_1, L_2, L_3: 0.7h, 0.33A

T_1, T_2, T_3: 240V/120V 100 VA/ϕ

CR_1, CR_2, CR_3: Full-wave Bridge Rectifier

P_1: Clark-Hess Wattmeter 255

P_2: General Electric Wattmeter - WM 5C

Current Probe: Tektronix P6302

Amplifier: Tektronix AM 503
Oscilloscope: Tektronix 7623A
Voltmeter: Hewlett-Packard 3400A
Spectrum Analyzer: Hewlett-Packard 3585A

Figure 4-9. Three-Phase System Test Circuit

The bridge rectifier and capacitor simulate the operation of solid-state ballasts by generating high harmonics with the voltage and current in phase. The phase measurement was made with the inductor and the bridge rectifier with the capacitor. This represents a circuit with the current and voltage out of phase with a non-sinusoidal current.

Section 5

RESULTS

FLUORESCENT BALLASTS

The ballasts are divided into three categories: 120-V two-lamp, 277-V two-lamp, and 277-V three-lamp ballasts. Three ballasts of each type were tested; the values listed are the average measured for the three units. Each group of solid-state ballasts is compared with a standard CBM core-coil ballast. The three-lamp solid-state ballast results are compared with results of tests on a two-lamp core-coil ballast and a one-lamp core-coil ballast. This latter configuration simulates the practice currently used to operate three-lamp fixtures since there are no three-lamp core-coil ballasts. The same F-40, T-12, rapid-start, cool-white lamps were used for each measurement, i.e., for the standard core-coil and all solid-state ballasts.

The second column in each of Tables 5.1, 5.2 and 5.3 lists the ANSI specifications appropriate for the CBM core-coil ballast operating F-40, T-12, fluorescent lamps. The values are provided for reference; no guidelines or ANSI specifications exist for solid-state ballast operation of fluorescent lamps. However, most circuit designs attempt to meet ANSI recommendations. The three columns on the right summarize the results of the three groups of solid-state ballasts, listing the minimum, maximum, and average value of each parameter. Parameters that depend on the number of lamps operating (e.g., input power and light output) are not averaged for the two- and three-lamp systems.

Ballast Input

Table 5-1 lists the electrical input to the ballast systems. LBL measured the input power and the power factors at minimum lamp wall temperatures of 39 and 50°C. At 39°C, the power and power factor were measured at the center design voltage and at ±10% about this voltage. The core-coil ballasts have a ±8% variation in power for a ±10% change in input voltage. Solid-state systems' output power for the ±10% input voltage varied as little ±1% and as much as ±25%.

The input power at the center design voltage varies considerably for different solid-state ballasts operating the same type of fluorescent lamps from 66 to 91 W. As lamp wall temperatures increased, the power to the solid-state ballast increased, in contrast to the decrease in the input power shown by the core-coil ballast systems. Solid-state ballasts 1, 6, and 9 behaved similarly to the core-coil systems.

Table 5-1

FLUORESCENT BALLASTS (SYSTEM INPUT)

Characteristic	Center Volt.	Core-Coil ANSI Spec.	Core-Coil 120-V 2-lamp	Solid-State 120-V 2-lamp					Core-Coil 277-V 2-lamp	Solid-State 277-V 2-lamp			Core-Coil 277-V 3-lamp	Solid-State 277-V 3-lamp	Summary		
				1	2	3	4	5		6	7	8		9	Min.	Ave.	Max.
[Lamp Temp.≡39°C]																	
Power (W)	90%		89	84	65	61	64	70	87	80	61	58	136	118	58	68	84
	100%		96	85	72	67	73	91	95	82	69	66	148	121	66	76	91
	110%		102	86	80	75	80	116	103	83	77	74	160	124	74	84	115
Relative Power Change	(%)		7	1	10	10	11	25	8	2	12	12	8	2	1	9	25
Power Factor	90%		0.99	0.99	0.92	0.90	0.91	0.96	0.99	0.95	0.95	0.81	0.99	0.96			
	100%	0.90	0.98	0.99	0.91	0.89	0.91	0.96	0.99	0.94	0.95	0.80	0.98	0.95	0.80	0.91	0.99
	110%		0.97	0.98	0.90	0.89	0.90	0.97	0.98	0.93	0.94	0.78	0.96	0.95			
Harmonics[a]	3rd(%)		12	9	33	20	28	16	7	13	28	22	4	10	9	20	33
	5th(%)		10	1	17	11	18	15	10	13	7	14	8	12	1	12	18
EMI																	
[Lamp Temp. ≡ 50°C]																	
Conducted (dBμA)			27	95	64	56	78	81	22	91	58	56		101	56	79	101
Radiated (Broad-band)(dBμV/m)			107	100	138	112	134	124	128	107	138	114		108	100	119	138
(Narrow-band) (dBμV/m)			72	104	134	104	130	113	70	105	134	106		106	70	115	134
Power (W)	100%		88	75	74	70	74	99	88	72	67	78	141	110	67	76	99
Power Factor		0.90	0.96	0.99	1.00	0.99	1.00	0.97	0.98	0.93	1.00	1.00	0.98	0.95	0.93	0.98	1.00
Relative Power Change (39°C to 50°C) (%)			-8	-12	+3	+4	+1	+9	-7	-12	+3	+18	-5	-9			

[a]Data is in terms of percentage of fundamental harmonics.

Table 5-2

FLUORESCENT BALLASTS (LAMP INPUT)

Characteristic [Lamp Temp. 39°C]	Center Volt.	ANSI Spec.	Core-Coil 120-V 2-lamp	Solid-State 120-V 2-lamp 1	2	3	4	5	Core-Coil 277-V 2-lamp	Solid-State 277-V 2-lamp 6	7	8	Core-Coil 277-V 3-lamp	Solid-State 277-V 3-lamp 9	Summary Min.	Ave.	Max.
Open Circuit Voltage (V)	90%	256	262	294	336	380[a]	427[b]		265	298	323	497[a]		461			
	100%	to	285	294	364	383[a]	487[b]		288	297	356	500[a]		461	294	393	500
	110%	330	307	294	380	380[a]	536[b]		309	295	375	500[a]		462			
Open Circuit Crest Factor	90%		1.5	1.5	1.4		1.3		1.6	1.3	1.4		1.3	1.3			
	100%	2.0	1.5	1.5	1.4		1.3		1.5	1.3	1.4		1.3	1.3	1.3	1.4	1.5
	110%		1.6	1.5	1.5		1.3		1.5	1.3	1.5		1.3	1.3			
Filament Voltage (V)	90%	2.5	3.1	3.3	3.2	(4.1)[c]						(40)[c]					
	100%	to	3.5	3.3	3.6	(4.6)						(4.5)					
	110%	4.0	3.9	3.3	4.0	(4.9)						(4.8)					
Lamp Crest Factor	90%		1.5	1.3	1.8	1.9	1.4	1.9	1.6	1.4	1.5	1.9		1.5			
	100%	1.7	1.7	1.4	1.8	1.9	1.5	1.8	1.7	1.4	1.6	1.9		1.5	1.4	1.6	1.9
	110%		1.8	1.2	1.8	1.9	1.5	1.8	1.7	1.4	1.5	2.0		1.5			

[a]The open-circuit waveshape is a 380-V pulse; thus, no crest factor could be measured.

[b]The first ballast tested for open-circuit voltage failed; thus, no further ballasts were tested.

[c]A voltage is applied only on starting; the value of the filament voltage at start is in ( ); the operating filament voltage is zero.

Table 5-3

FLUORESCENT BALLASTS (LAMP AND SYSTEM OUTPUT)

Characteristic	Center Volt.	ANSI Spec.	Core-Coil 120-V 2-lamp	Solid-State 120-V 2-lamp 1	2	3	4	5	Core-Coil 277-V 2-lamp	Solid-State 277-V 2-lamp 6	7	8	Core-Coil 277-V 3-lamp	Solid-State 277-V 3-lamp 9	Summary Min.	Ave.	Max.
[Lamp Temp. ≡ 39°C]																	
Light Output (lm)	90%	4370	5740	5630	5050	4760	5130	4740	5570	5740	4790	4630	8470	9080			
	100%	5830	6100	5720	5590	5330	5830	6190	5980	5800	5320	5210	8970	9250	5210	5670	6190
	110%	7290	6340	5740	6080	5920	6420	7600	6300	5841	5820	5810	9350	934			
Ballast Factor	100%	0.925	0.968	0.907	0.887	0.846	0.925	0.982	0.949	0.920	0.845	0.826	0.949	0.978	0.826	0.902	0.978
Light Output Regulation (%)	90%	-25	-6	-1	-10	-11	-12	-23	-7	-1	-10	-11	-6	-2	-23	-9	-1
	100%	+25	+4	0	+9	+11	+11	+23	+5	+1	+9	+12	+4	+1	+23	+9	0
Percent Flicker (%)	100%		31	0	5	33	4	32	30	0	3	30	28	4	0	12	33
System Efficacy (lm/W)	90%		65	68	78	79	80	68	64	72	78	79	62	77			
	100%		64	68	77	79	80	68	63	71	77	79	61	76	68	75	80
	110%		62	67	77	79	80	66	61	70	76	79	58	75			
[Lamp Temp. ≡ 50°C]																	
Light Output (lm)	100%		5510	5290	5350	5070	5540	6700	5400	5280	4890	4810	824	8940	4890	5370	6700
Ballast Factor	100%		0.875	0.840	0.849	0.804	0.879	1.064	0.857	0.853	0.776	0.763	0.872	0.946	0.763	0.864	1.064
System Efficacy (lm/W)	100%		62	70	73	72	75	66	60	71	74	63	58	79	63	71	79
Relative Change of Light with Temp. (39-50°C) (%)			-10	-7	-4	-5	-5	+8	-10	-9	-8	-8	-8	-3	-3	-5	-10
Rel. Unit Change Efficacy with Temp. (39-50°C) (%)			-4	3	-6	-10	-6	-3	-5	0	-4	-21	-4	+3	0	-5	-21
Relative Efficacy Respect to Core (%)																	
@ 39°C			100	106	121	124	125	107	100	113	122	126	100	126	106	119	126
@ 50°C			100	114	119	116	122	108	100	119	123	105	100	135	105	118	135

Lamp Input

Table 5-2 lists the lamp operating parameters for each type of ballast. The open-circuit voltage is a measure of the maximum starting voltage applied to the lamp. No open-circuit voltage is listed for ballast 5. The first measurement caused a ballast failure due to the removal of one lamp, and researchers believed that the other ballasts would fail if this parameter were measured. The open-circuit voltage measured for ballasts 3 and 8 consisted of a voltage pulse applied during starting. The shape of the pulse made determination of the open-circuit crest factor impossible. The starting voltage for all the solid-state ballasts, except units 1 and 6, exceeds the maximum recommended starting voltage. The filament voltages at start are within the ANSI recommended values, except for unit 4. For ballasts 3 and 8, the filament voltages at starting voltages are in parenthesis. These particular ballasts eliminate the filament voltage after the lamps have been ignited, and special techniques were required to record the filament voltages when the units were started. The lamp current crest factors are within or near the ANSI recommended values for all the solid-state ballast designs.

Lamp Output

Table 5-3 lists the lamp and system output characteristics. The changes in solid-state ballast light output for a variation in input voltage of ±10% are all within the required ±25% of the ANSI recommendations. It is interesting to note that some ballasts have highly regulated circuits, with a near-zero change in light output, whereas others are very loosely regulated, showing a ±22% change.

The percent flicker for some solid-state systems is as high as for core ballasts that operate lamps at 60 Hz, but others virtually eliminate flicker.

The ANSI-specified ballast factor is 95 ± 2-1/2%. The standard core-coil CBM ballast with two 40-W, T-12 lamps conforms to this standard. The ballast factors for the solid-state ballasts range from 0.826 to 0.978. No ANSI standards exist for ballast factor at 50°C lamp wall temperature. However, evidence shows that ballast factors decrease at 50°C, which is a common operating condition. Researchers determined the ballast factors at 50°C based on rated light output specified in manufacturers' catalogs, i.e., the light output measured under ANSI conditions and at a 25 ± 1°C ambient.

The system efficacy for each solid-state ballast system is nearly constant for the ±10% variation in input voltage. Different systems' measured efficacies vary from 68 to 80 lm/W. The ballast systems with lower efficiencies are those designed to dim lamps. One of the dimming ballasts has the best regulation, least percent flicker, and improved thermal performance compared with the other solid-state and core-coil ballasts. At the higher lamp wall temperature (50 °C), light output decreased, except ballast 5's. On the average, the solid-state ballast system light output decreased half as much as those of the core-coil systems.

The bottom row in Table 5-3 shows system efficacy at lamp wall temperatures of 39 and 50 °C. These data are important because they are the basis for determining system cost-effectiveness, given the environment in which the system is to operate. Some solid-state ballasts' (1, 6, and 9) have an improved relative efficacy at the higher temperature; others (3 and 8) decreased significantly.

HIGH-PRESSURE SODIUM VAPOR BALLASTS

Table 5-4 lists the data measured for the four high-pressure sodium vapor (HPS) lamps. LBL compared each solid-state ballast with a core-coil ballast specified to operate the same HPS lamp.

The table shows the power, power factor, and light output at the center design voltage and at ±10% about that voltage for each ballast system. LBL tested three ballasts of each type; the results in the table are average values.

The parameters that distinguish HPS lamps with core-coil ballasts and solid-state designs are percentage regulation and flicker. The solid-state system's input power and light output vary little at input voltages ±10% about the center design voltage. For the solid-state ballasts 1, 2, and 3, which operate the lamps at high frequency (20 to 30 kHz), flicker is nearly eliminated, i.e., reduced from 90% to less than 5%. Unit #4 drives the lamp at 60 Hz with a square wave.

The high-wattage HPS solid-state ballast systems have the greatest efficacy, ranging from 83 lm/W for the 150-W lamp to 112 lm/W for the 400-W lamp. The core-coil ballast also shows this trend, ranging from 78 lm/W to 106 lm/W. The system efficacies of the solid-state ballast systems are greater than those of the corresponding core-coil ballast systems by a factor of 5 to 13%.

Table 5-4

HIGH-PRESSURE SODIUM VAPOR BALLASTS

Characteristic	Center Volt.	Core-Coil 400-W lamp	Solid-State 400-W lamp	Core-Coil 200-W lamp	Solid-State 200-W lamp	Core-Coil 150-W/55-V	Solid-State 150-W/55-V	Core-Coil 150-W/100-V	Solid-State 150-W/100-V
			1		2		3		4
Power (W)	90%	411	444	236	234	152	143	159	141
	100%	446	454	259	238	191	150	178	135
	110%	492	453	281	241	244	154	200	136
Power Factor	90%	0.98	0.79	1.00	0.98	0.89	0.97	0.92	0.60
	100%	0.98	0.78	1.00	0.97	0.83	0.97	0.88	0.57
	110%	0.96	0.77	0.98	0.97	0.74	0.95	0.83	0.58
Ballast Factor	100%	0.942	1.014	0.945	0.979	0.933	0.784	0.936	0.750
Light Output (lm)	90%	42,480	49,490	18,160	21,370	10,560	12,270	12,320	11,910
	100%	47,100	50,680	20,790	21,540	14,930	12,550	14,040	11,250
	110%	53,050	50,200	22,570	21,750	21,010	12,580	16,000	11,140
Light Output Regulation (%)	90%	-10	-2	-13	-1	-29	-3	-13	6
	110%	13	-1	9	+1	40	0	13	-1
Percent Flicker (%)	100%	93	0	84	4	93	5	78	26
Harmonics[a] 3rd (%)		8	59	5	13	27	28	60	90
5th (%)		2	16	1	15	5	7	2	74
Lamp Current Crest Factor	100%	1.7	1.3	1.5	1.7	1.4	1.6	1.6	1.1
System Efficiency (lm/W)	90%	103	112	77	91	70	85	78	84
	100%	106	112	80	91	78	84	79	83
	110%	108	111	80	90	86	82	80	82
Relative Efficiency (%)	90%	100	108	100	119	100	122	100	108
	100%	100	106	100	113	100	107	100	105
	110%	100	103	100	112	100	95	100	102

[a]Data is in terms of percentages of fundamental harmonics.

STATIC CONTROLS

Two-Lamp, F-40, Rapid-start

Table 5-5 lists the results for the static controls connected either to the input or output side of a core-coil, two-lamp, rapid-start fluorescent ballast. These controls are designed to reduce fluorescent lamp light output by either 30 or 50%. LBL tested two units of each type. The table lists the average of the two. The columns on the right of the table summarize the results of the 30 and 50% static controls. The results show a near-linear decrease in power and light output, within the error of measurement of ±2%. Systems 1 and 4 show increased efficacy. However, this increase is obtained at the expense of reducing the filament voltage (2.3 V) and the power factor. Two of the 50% static controls reduced efficacy by 7 and 14%.

F-96, Instant-Start Lamps

Table 5-6 lists the results for the static controls designed to reduce light levels 30% or 50% for two F-96, instant-start, 8-ft fluorescent lamps. LBL tested three units of each device. The table lists the average of the three measurements. In general, the percent decrease in light output equals the percent decrease in input power. That is, adding the static controller maintains an efficacy of 69 lm/W within the error of the measurement (±2%). Instant-start lamp electrodes are not externally heated; thus, there are no filament voltage measurements.

DYNAMIC CONTROLS

Dimming Core-Coil Ballasts

Table 5-7 lists the measurements of dynamic controls that can dim fluorescent lamps over a range of light levels. Devices 1 through 4 are systems that change the light output by varying the input power to standard core-coil ballasts. Devices 5 through 8 are solid-state ballast systems that can vary the light output by control signals fed into the ballasts' internal circuitry. LBL tested three units of each two-lamp system; table results are averages. The data for the control devices with the 16 and 20 A capacities were obtained from measurements on one two-lamp system. Researchers measured all parameters at the maximum, minimum, and at midlight output. The minimum level was the lowest level attainable at stable lamp operation, i.e., without striations or other gross indications that the charge was intermittently extinguished.

Table 5-5

STATIC CONTROLS (2-LAMP, 40-W)

Characteristic	Core-Coil 120-V 2-lamp	Controller						Summary					
		30%	30%	30%	50%	50%	50%	30%			50%		
		1	2	3	4	5	6	Min.	Ave.	Max.	Min.	Ave.	Max.
Power (W)	95	61	63	60	45	42	45	60	61	63	42	44	45
Power Factor	0.98	0.66	0.95	0.95	0.61	0.83	0.87	0.66	0.85	0.95	0.61	0.77	0.87
Light Output (lm)	6100	4060	4060	3850	2690	2350	270	3850	3990	4060	2350	2670	2960
Filament Voltage (V)	3.6	2.3	3.5	3.5	2.3	3.5	3.5	2.3	3.1	3.5	2.3	3.1	3.5
Percent Flicker (%)	30	32	27	27	39	31	31						
Harmonics[a] 3rd (%)	13	29	25	28	36	40	37						
5th (%)	10	4	12	10	3	11	12						
EMI													
Conducted (dB A)	27	25	22	22	23	18	19						
Radiated (dB V/m)													
Narrow-band	72	69	71	70	68	68	71						
Broad-band	107	105	107	107	103	105	105						
System Efficiency (lm/W)	64	67	65	64	65	56	60	64	65	67	56	60	65
Relative Change (%)													
Power	0	-36	-34	-37	-53	-55	-52	-34	-36	-36	-55	-53	-53
Light	0	-33	-33	-37	-51	-62	-56	-33	-34	-33	-62	-57	-51
Efficiency	0	4	2	0	2	-14	- 7	0	1	4	-14	- 7	2

[a]Data is in terms of percentages of fundamental harmonics.

Table 5-6

STATIC CONTROLS (F-96, INSTANT-START LAMPS)

Characteristic	Core-Coil 120-V 2-lamp	Controller					Summary					
		30%	30%	30%	50%	50%	30%			50%		
		7	8	9	10	11	Min.	Ave.	Max.	Min.	Ave.	Max.
Power (W)	167	110	118	122	91	106	110	117	122	91	99	106
Power Factor	0.99	0.86	0.83	0.87	0.72	0.74	0.83	0.85	0.87	0.72	0.73	0.74
Light Output (lm)	11,540	7730	8080	8570	6030	7230	7730	8130	8570	6030	6630	7230
Percent Flicker (%)	30	26	23	24	20	22						
Harmonics 3rd (%)	15	19	17	17	19	17						
5th (%)	7	6	6	6	5	5						
System Efficiency (lm/W)	69	70	68	70	67	68	68	69	70	67	68	68
Relative Change (%)												
Power	0	-34	-29	-27	-46	-37	-27	-30	-34	-46	-42	-37
Light Output	0	-33	-30	-26	-48	-37	-26	-30	-33	-48	-43	-37
Efficiency	0	2	-1	2	-4	0	-1	1	2	- 4	- 2	0

[a]Data is in terms of percentage of fundamental harmonics.

Table 5-7

DYNAMIC CONTROLS (TWO- AND THREE-LAMP, 40-WATT)

Characteristic	Light Level	Core-Coil 120-V 2-lamp	Controller 120-V/0.8-A 1	Controller 120-V/16-A 2	Controller 120-V/20-A 3	Controller Variac 4	Solid-State Ballasts 120-V/0.7-A 5	Solid-State Ballasts 277-V/0.3-A 6	Solid-State Ballasts 120-V/0.8-A 7	Solid-State Ballasts 277-V/0.5-A 8
System Input Power (W)	max.	94	94	100	100		83	82	90	121
	mid.		73	80	50		50	47	48	59
	min.		38	48	17		22	19	16	41
Power Factor	max.	0.97	0.98	0.91	0.94		0.99	0.93	0.96	0.96
	mid.		0.86	0.52	0.61		0.98	0.89	0.97	0.93
	min.		0.71	0.66	0.63		0.97	0.75	0.87	0.88
Harmonic† (%) 3rd	max.	12	10	35	33	12	9	13	16	9
	mid.		35	52	54	19	3	24	11	21
	min.		42	53	56	24	9	50	24	28
Ballast Input Voltage (V)	max.	120	117	119	119	120				
	mid.		95	92	87	90				
	min.		91	87	84	84				
Power (W)	max.	94	91	100	98	94				
	mid.		59	63	47	73				
	min.		31	48	15	53				
Light Output (lm)	max.	6100	5910	6410	6180	6100	5690	5950	6210	9048
	mid.		3960	4740	3390	4900	2660	2780	2890	3500
	min.		2010	3070	602	3560	360	390	430	2060
Filament Voltage (V)	max.	3.5	3.4	3.4	3.4	3.5	3.3	3.3	4.6	2.5
	mid		2.7	3.0	2.5	2.4	4.1	3.8	5.1	2.8
	min.		2.7	2.4	2.5	2.5	3.0	3.1	4.5	2.8
System Efficiency[a] (lm/W)	max.	65	63 (0.97)	64 (105)	62 (101)	65 (100)	69 (100)	73 (100)	69 (100)	75 (100)
	mid.		55 (0.65)	59 (78)	68 (56)	67 (80)	53 (47)	59 (47)	61 (47)	59 (39)
	min.		54 (0.33)	65 (50)	37 (10)	66 (58)	16 (6)	21 (7)	27 (7)	50 (23)

[a]The numbers in parentheses are ratio of full light output.
†Data is in terms of percentage of fundamental harmonics.

System 4 simulates a device that reduces the magnitude of the input voltage to the ballast. LBL used a Variac and made measurements at the input side of the ballast. Systems 1, 2, and 3 were measured on the input side of the control and on the input to the ballast. All controllers operated standard core-coil, two-lamp, F-40, rapid-start fluorescent ballasts. Note that devices 2 and 3 are rated at 16 and 20 A. Since the input currents for two-lamp systems are rated at 0.8 and 0.4 A for 120-V and 277-V systems, the control devices are designed to operate two- to four-lamp systems and 25- to 50-lamp systems for the 16- and 20-A devices, respectively.

The general trends shown in Table 5-7 indicate that as light levels are reduced, power factor, filament voltage, and system efficacy all decrease. The systems also have a dimming range between 100 and 50% of full light output. Device 3 dimmed the fluorescent lamps down to 10% of full light output, but that unit was designed to control between 25 and 50 lamps and could achieve this dimming range for this light electrical load.

The solid-state ballast dimming system power factor decreased slightly, but the systems maintained near-full filament voltage at low light output. All the two-lamp systems could be dimmed to at least 7% of full light level. The three-lamp systems could be dimmed to 23% of full light output. The system efficacy row shows the percent of full light output in parentheses, which allows comparison of system efficacies at the same relative light level. Figure 5-1 plots the dimming performances of dynamic control devices that control the input to a core-coil ballast. The cross in the figure's upper right is the system's light output and power input without any add-on control. The dashed line passing through the origin represents a constant system efficacy of 65 lm/W. A solid line is drawn between the averages of the experimental points obtained from the three devices. At full light output, the add-on devices decrease efficacy by 2-4%, and at about 58% of full light output, the efficacy reaches a maximum about equal to the system efficacy without the devices.

Dimming Solid-State Ballasts

Figure 5-2 plots results for the solid-state ballast systems operating two fluorescent lamps. The data from the three ballasts fall on the same straight line. At full light output, solid-state ballast system efficacy is greater than standard core-coil ballast system efficacy. Efficacy decreases linearly as the fluorescent lamps are dimmed to the minimum light output.

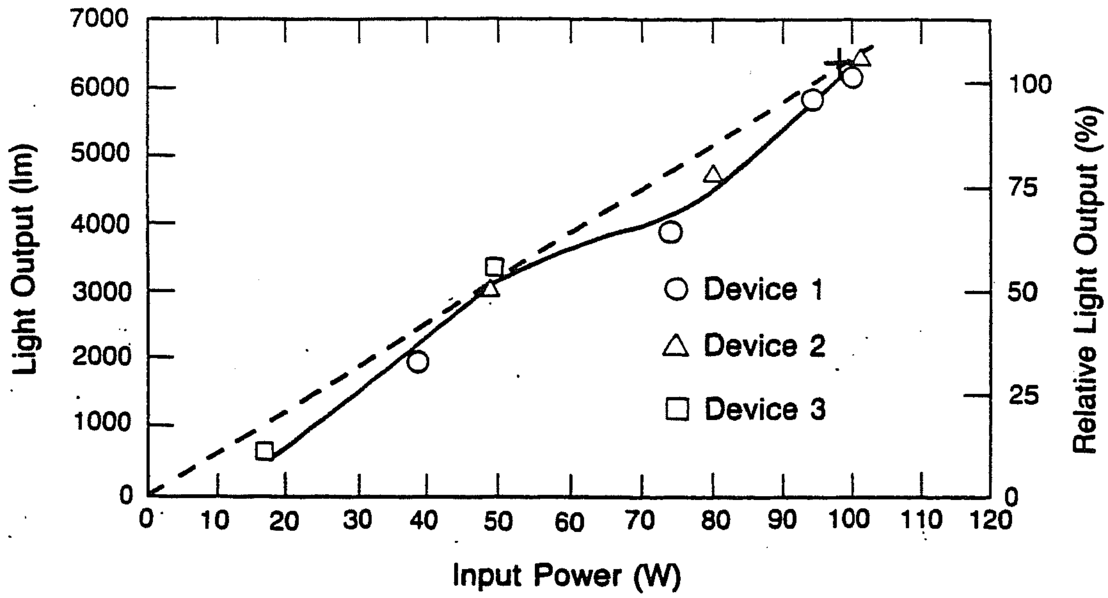


Figure 5-1. Light Output vs. Power Input for Core-Coil Ballast Systems

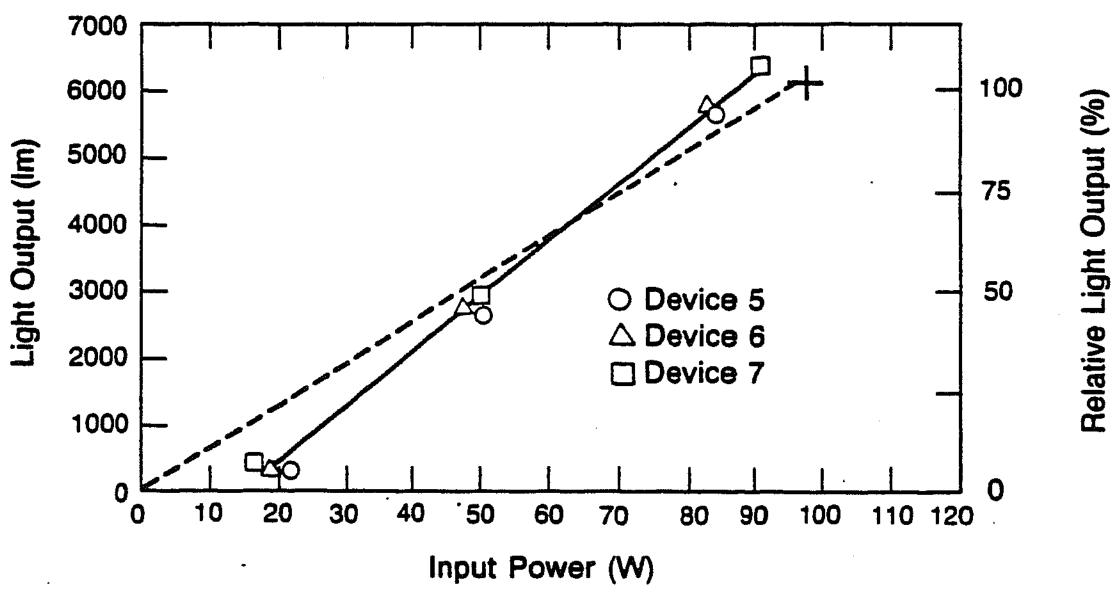


Figure 5-2.
Light Output vs. Power Input for Solid-State Ballast Dimming Systems

Figure 5-3 plots the results for the three-lamp solid-state dimming ballast systems. As with the two-lamp system, the efficacy decreases linearly for the lower light levels. This figure compares the solid-state system with the three-lamp core-coil ballast systems (using a one-lamp and a two-lamp ballast).

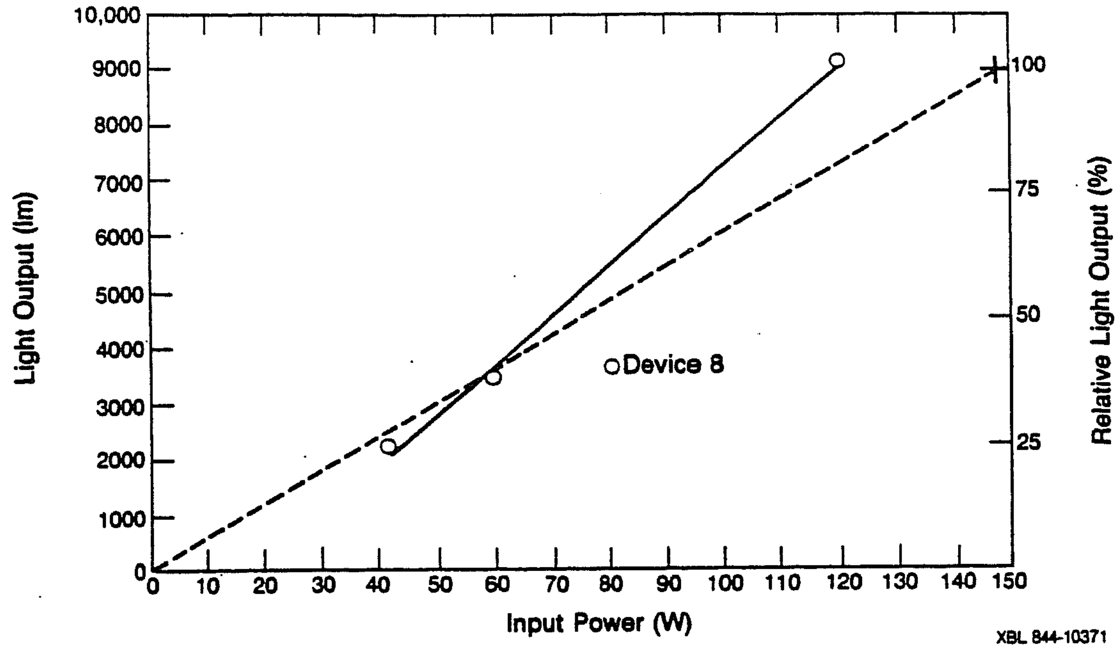


Figure 5-3.
Light Output vs. Power Input for Three-Lamp
Core-Coil and Solid-State-Ballast Dimming Systems

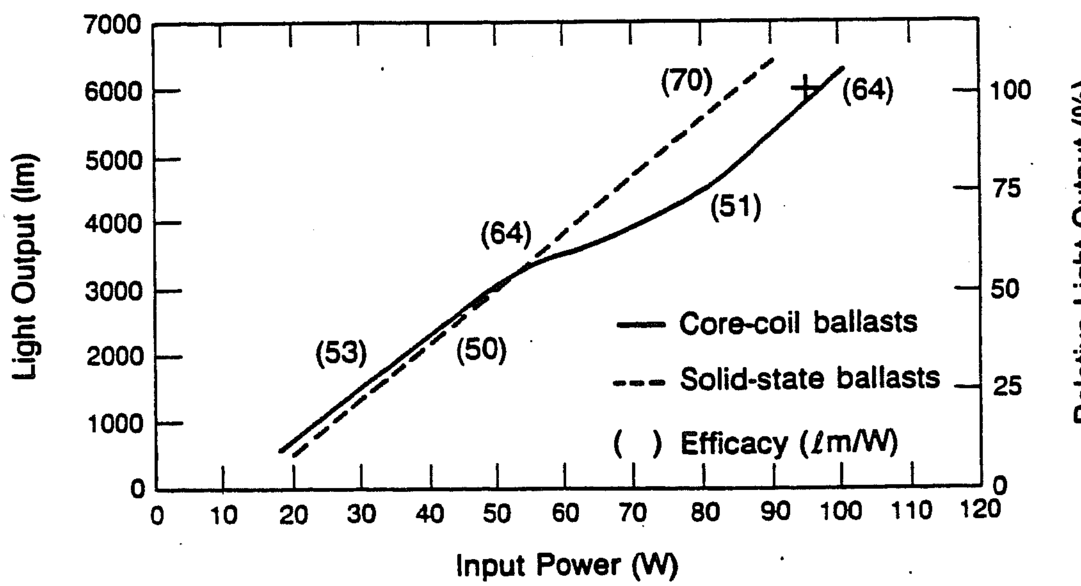


Figure 5-4.
Light Output vs. Power Input for Two-Lamp Core-Coil
and Solid-State Dimming Systems

Figure 5-4 compares the efficacies of the add-on dynamic controllers and the solid-state ballast dimmers, showing system efficacies at various light levels in parentheses. The solid-state ballasts are more efficacious, providing between 66 and 100% light output.

POWER FACTOR WITH THREE-PHASE CIRCUITS

Table 5-8 shows the circuit parameter measurements for the delta-wye system that result from high resistive, inductive, and component-generating harmonics. The pure resistive load results in a unity power factor in the secondary and a near unity in the primary circuit. The leg currents in the balanced three-phase circuit are out of phase by 120°, as shown in Figure 5-5, which results in a near-zero current in the neutral. The table shows this current to be 0.0079 A or 0.5% of leg current (0.15 A). Figure 5.6 shows the wave traces in the primary and secondary circuits. The inductive loads, columns 2 and 3 of Table 5-8, show an out-of-phase relationship of about 84° in the secondary. The 80-V inductor circuit shows virtually no wave distortion, as evidenced by the low third and fifth harmonics (see waveform trace, Figure 5-7). Increasing the voltage to 120 V across the inductor causes saturation, which results in some wave distortion as evidenced by an increase in the third harmonic to 3.4%. The neutral current increases to about 10% of the leg current. Note the slight distortion of the current waveform in Figure 5-8.

The bridge-rectified capacitor circuit distorts the waveshapes and generates large third and fifth harmonics, well above those generated by the solid-state ballasts (see Table 5-1). The current in the neutral exceeds the current in any one leg. The waveforms are shown in Figure 5-9 with a "soft" voltage source (small transformer); a highly nonsinusoidal current clips the secondary voltage waveform. The "hard" primary voltage source is not distorted.

The factors reflected through the delta-wye system to the primary are the phase shifts and the fifth harmonic. The third, ninth, twelfth, etc., harmonics are contained and circulated in the primary transformer. Thus, they will not affect the generating source but will heat the transformer. Figure 5-10 shows the waveforms for this system.

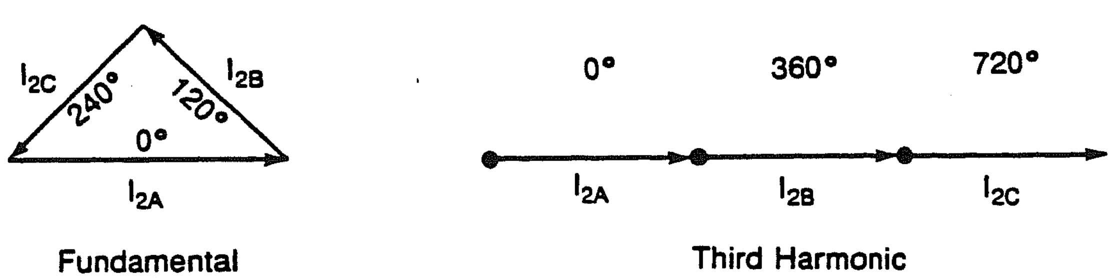


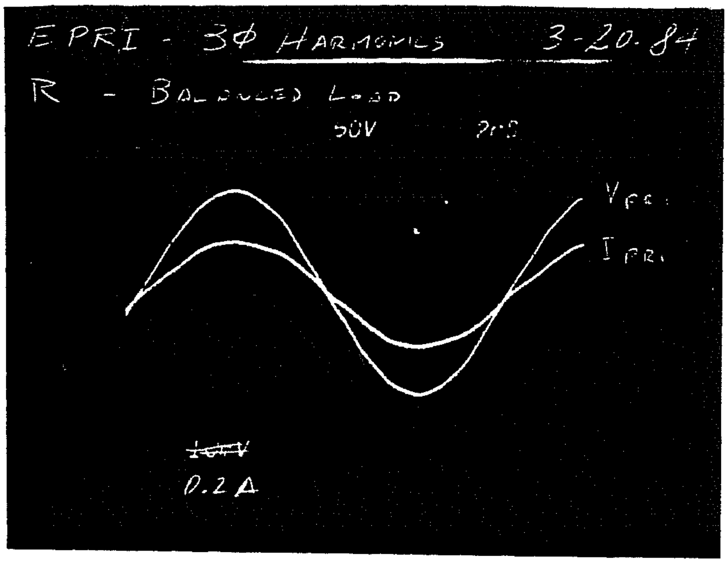
Figure 5-5. Vector Sum of Fundamental and Third Harmonics

Table 5-8

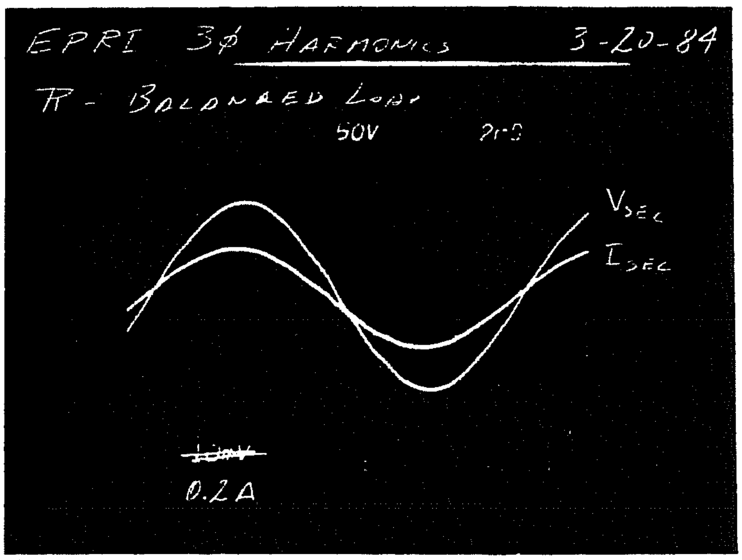
WAVESHAPES AND VOLTAGE-CURRENT RELATIONSHIPS FOR INDUCTIVE (NONSATURATING) LOAD

	Type of Load				
	R	R,C	L(80-V)	L(120-V)	R,L,C
Balanced Secondary					
Primary power factor	0.980	0.870	0.208	0.213	0.669
Secondary power factor	1	0.667	0.102	0.107	0.562
Secondary leg current (A)	0.150	0.344	0.273	0.438	0.445
Secondary neutral current (A)	0.0079	0.61	0.007	0.044	0.60
Primary 3rd harmonic current (%)	0.5	2.0	0.4	1.9	2.5
Secondary 3rd harmonic current (%)	0.6	82.9	0.5	3.4	50.5
Primary 5th harmonic current (%)	2.6	47.9	1.6	3.7	28.9
Secondary 5th harmonic current (%)	0.4	54.7	0.3	1.7	33.0
Unbalanced Secondary					
Primary 3rd harmonic current (%)	1.8	77.2	1.1	4.7	43.7
Primary 5th harmonic current (%)	5.4	52.3	2.5	5.4	29.8

Figure 5-11 shows the harmonic spectrum of the rectifier-filter capacitor (simulated solid-state ballast) system. Figure 5-11a shows the primary current, with the small third, ninth, etc., harmonics. Part b shows the large odd harmonics flowing in the secondary legs. The large third, ninth, etc., harmonics that flow through the secondary neutral are shown in part c. The other odd harmonics do not significantly contribute to the neutral current.

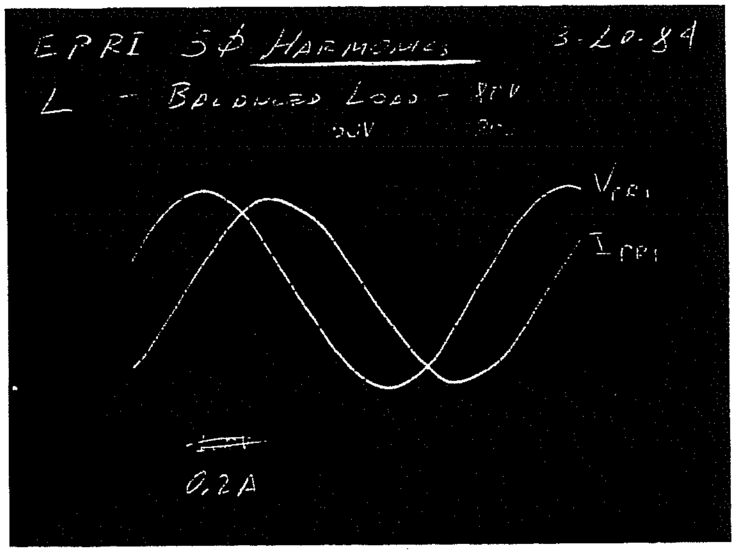


A. Primary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

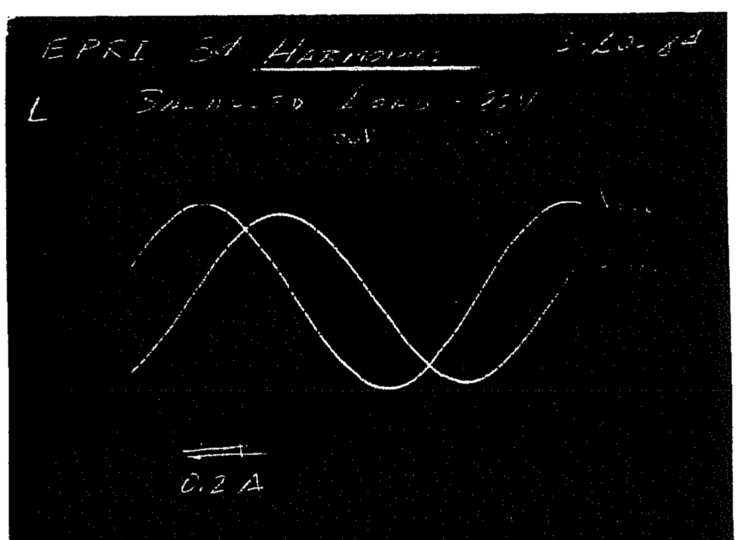


B. Secondary: Abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

Figure 5-6. Waveshapes and voltage-current relationship for resistive load. Current voltages are in phase.

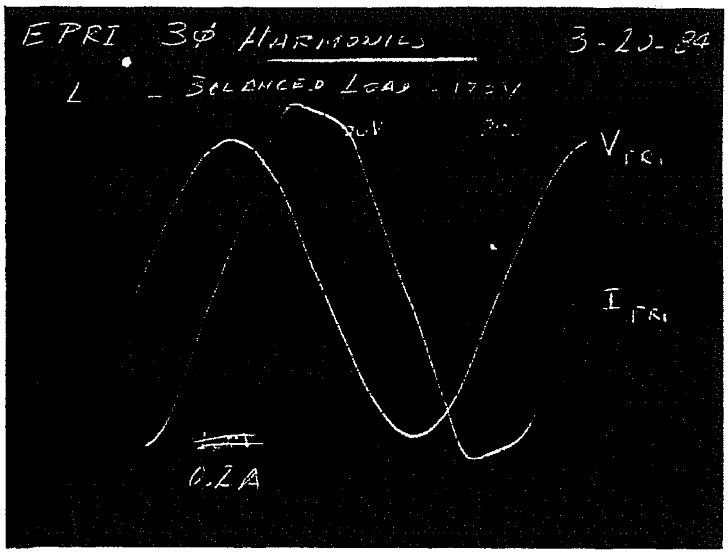


A. Primary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

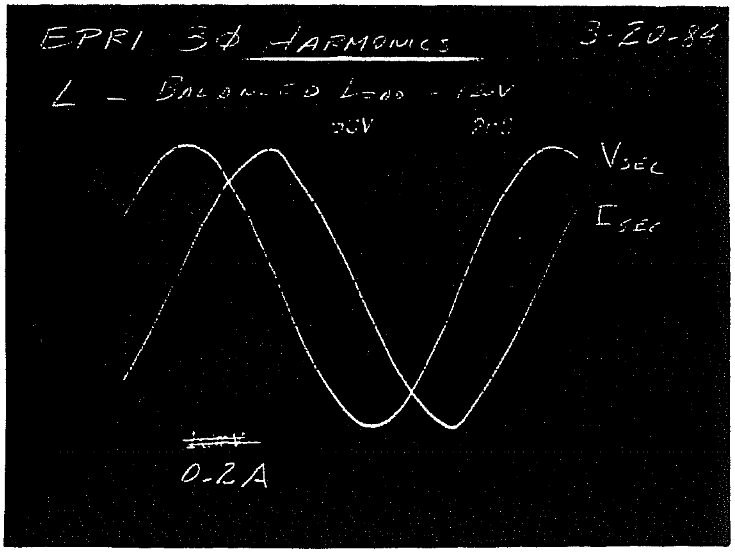


B. Secondary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

Figure 5-7. Waveshapes and voltage-current relationship for inductive (nonsaturating) load. Current lags votage by 90°.

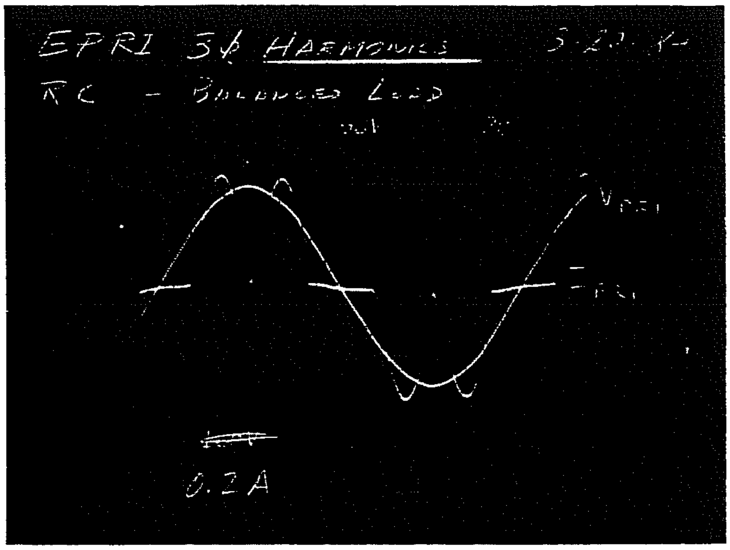


A. Primary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

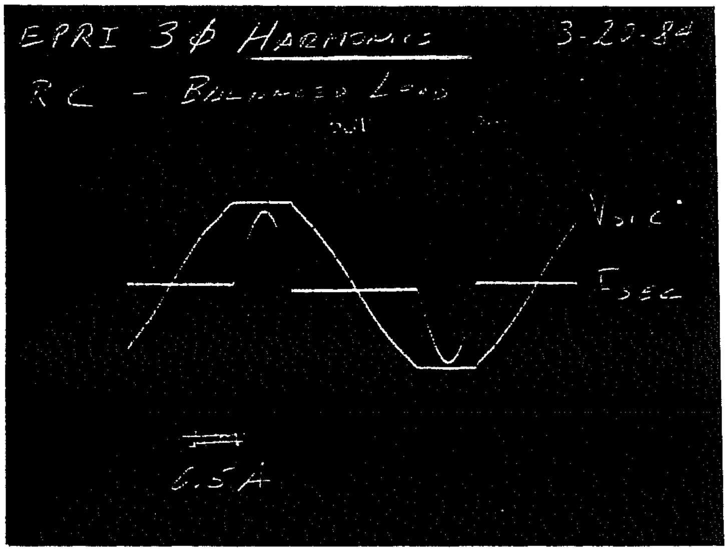


B. Secondary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

Figure 5-8. Waveshapes and voltage-current relationship for inductive (saturated) load. Current lags voltage by about 90°, and wave shape is slightly distorted.

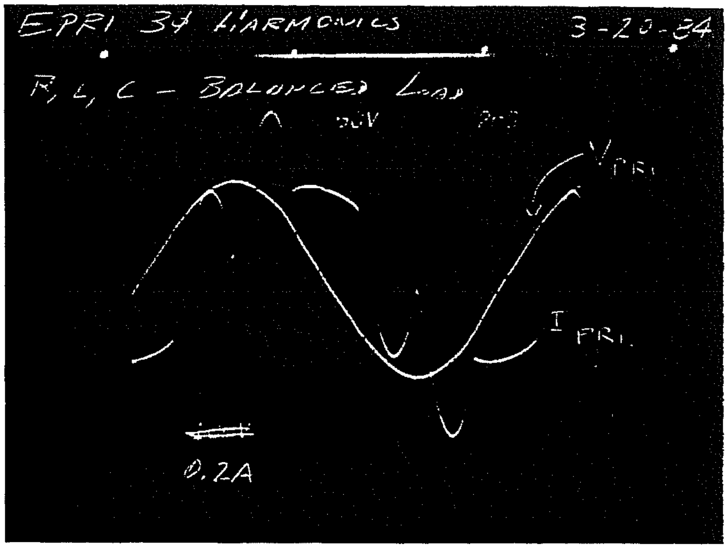


A. Primary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

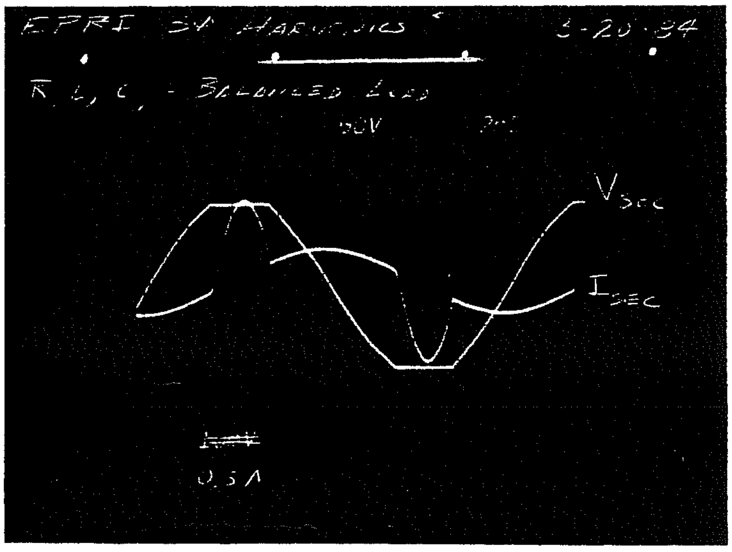


B. Secondary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.5 A/div.

Figure 5-9. Waveshapes and voltage-current relationships for rectified filter, capacitor-resistive load. Current in phase with voltage, with high distortions.

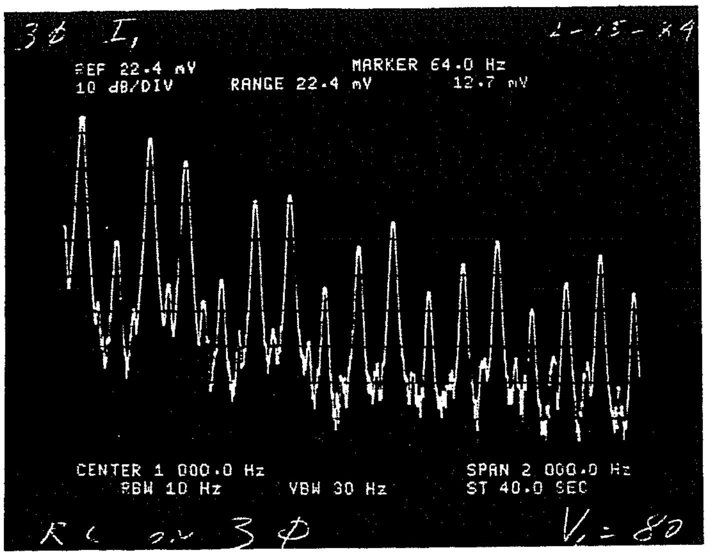


A. Primary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.2 A/div.

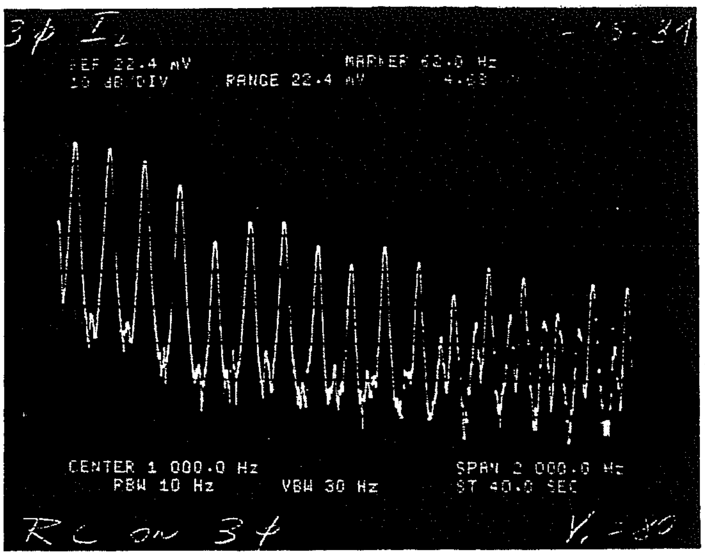


B. Secondary: abscissa, 2 msec/div; ordinate, V = 50 V/div, I = 0.5 A/div.

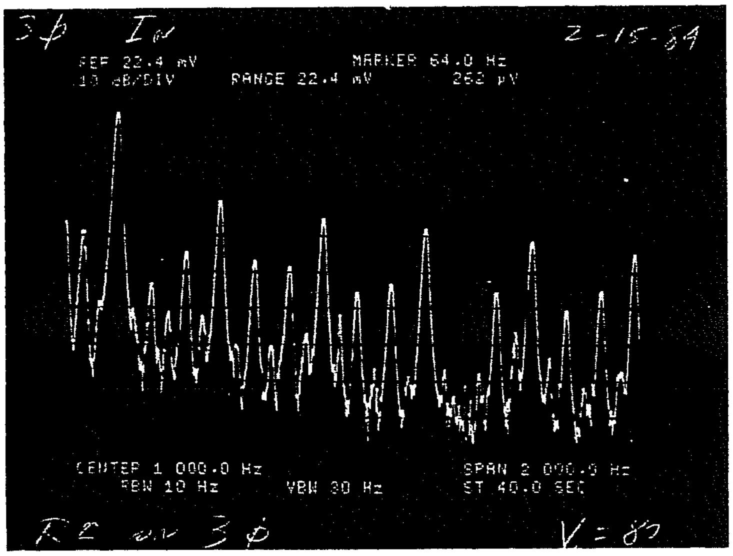
Figure 5-10. Waveshapes and voltage-current relationship for inductive plus rectifier filter, capacitor resistive load. Current lags voltage in addition to distorted wave shapes.



A. Primary current: abscissa, 0-2000 Hz; ordinate, 10 dB.

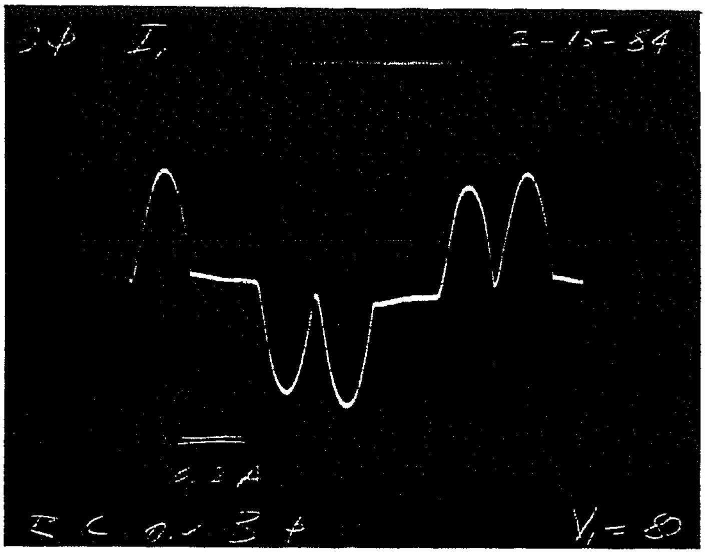


B. Secondary current: abscissa, 0-2000 Hz; ordinate, 10 dB.

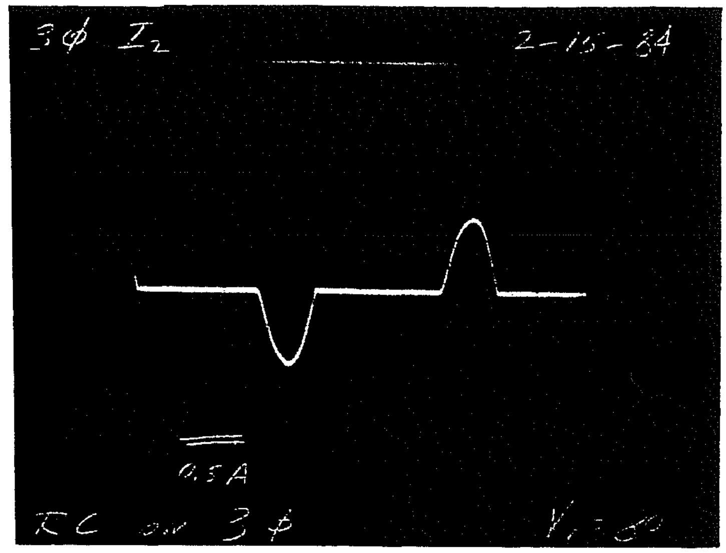


C. Secondary neutral leg current: abscissa, 0-2000 Hz; ordinate, 10 dB.

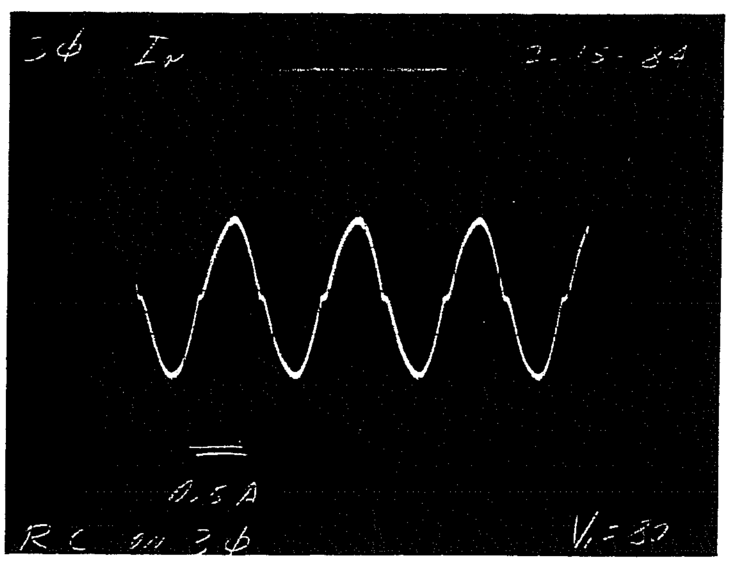
Figure 5-11. Harmonic content in the primary, secondary, and neutral leg for the rectifier filter, capacitor resistive load.



A. Primary current: abscissa, 2 msec/div; ordinate, 0.2 A/div.



B. Secondary leg current: Abscissa, 2 msec/div; ordinate, 0.5 A/div.



C. Secondary neutral current: abscissa, 2 msec/div; ordinate, 0.5 A/div.

Figure 5-12. Low-frequency current waveforms for the rectified filter, capacitor-resistive load in the Delta-wye circuit.

Section 6

DISCUSSION

FLUORESCENT BALLASTS

Lighting Applications and Design

Factors most important to lighting designers are electrical input, ballast factor, power factor, light output, system efficacy, and cost, as well as changes in performance as functions of lamp wall temperature. Electrical input is important for sizing wiring and controls (i.e., circuit breakers). Light output is important for calculating the necessary light level. Efficacy and component cost determine a lighting system's economics. The wide variations in ballast system performance clearly show that designers need more accurate information on these factors. Individual performance variations do not necessarily indicate good or bad solid-state ballasts, but can determine the most suitable ballast for a particular application.

Old lighting designs often overilluminate. For retrofits, designers may select systems having lower ballast factors, hence reducing power requirements and giving less light. Designers must know a system's ballast factor to determine how much the system will reduce light.

Systems with higher ballast factors may be more suitable for renovations and new buildings. Because fewer fixtures will be required to supply the designed illumination levels, fewer ballasts and lamps will be needed to meet lighting requirements.[7]

Table 6-1 lists unit costs of ballasts. A current strategy of solid-state ballast manufacturers is to introduce ballasts that operate three and four F-40 lamps. There are no core-coil three- or four-lamp ballasts, and a three- or four-lamp fixture uses two ballasts: a one-lamp and two-lamp or two two-lamp ballasts, respectively. The three- and four-lamp solid-state ballasts improve relative efficacy and reduce initial costs. Note that the three-lamp ballast costs slightly more than a two-lamp ballast (compare ballasts 1 and 6 with ballast 9 in the table).

Ballast and Lamp Reliability

Core-coil ballasts may last 10 to 12 calendar years, or more than 45,000 hours of operation. F-40, rapid-start, fluorescent lamps have a life expectancy of 20,000 h. Lamp operation, i.e., starting voltage, crest factor, and filament voltage, affect lamp life.

Table 6-1

UNIT COST OF BALLASTS

Ballast Type	Unit Cost ($)
120-V CMB Core-Coil	14
120-V Solid-State	
1[a]	58
2	38
3	22
4	24
5[a]	50
277-V CBM Core-Coil	14
277-V Solid-State	
6[a]	58
7	39
8	22
9[a]	62
277-V, One- and Two-Lamp Core Coil	24

[a]Dimming ballasts.

All the solid-state ballasts supply a suitable filament voltage during starting, which should ensure that the starting conditions will not curtail lamp life. The open-circuit voltage for most of the solid-state ballasts exceeds ANSI recommendations. However, because a suitable filament voltage is applied under normal conditions at a minimum lamp wall temperature greater than 50°F, the lamp will start before the maximum open-circuit voltage is reached. The higher starting voltage will start fluorescent lamps at ambient temperatures below 50°F. One exception is ballast 4, the filament voltage of which is only 1.6 V. Ballast 4's filament voltage and high open-circuit voltage indicate that the high fields applied during starting will probably reduce lamp life.

Solid-state ballasts 3 and 8 have circuitry that removes the filament voltage during operation, which may adversely affect lamp life. However, they save energy, and there may be a trade-off between lamp life and energy savings. However, no data exist for determining the percent reduction in lamp life. Some core-coil ballast/lamp systems operate at 60 Hz without filament power after starting. Manufacturers have derated the lives of these lamps by 25% when the lamps are operated this way. Users could apply the same derating to solid-state ballast systems that remove filament power.

In general, the near-constant performance of solid-state systems at ±10% of design voltage and 50°C lamp wall temperature indicates stable circuit design. One exception was the large variation in light output with ballast 5 at ±10% input voltage. This variation suggests an instability; a voltage change by more than +10%, could induce a runaway condition. Researchers confirmed this problem when they measured the open-circuit voltage (with one lamp removed); the ballast failed. Because ballasts and lamps are installed "hot," this ballast may tend to fail when users change lamps or if one lamp fails. Changing lamps or operating a two- lamp ballast with one lamp removed is one reliability test for solid-state ballasts.

None of the LBL tests can validate the long-term reliability of the tested devices. The only measure of long-term reliability is reviewing installation failure data, which should be available from the ballast manufacturers.

Electrical Supply

Power factor and harmonic content affect the electrical supply source. The experiment with the three-phase delta-wye circuit showed that reduced power factors resulting from phase shifts are transmitted to the electric supply. The harmonics generated in the secondary circuit, particularly the third harmonic, have no effect on supply. Thus, solid-state ballasts must be designed with the voltage and current in phase. Waveshapes are less important, particularly shapes that generate the third, ninth, twelfth, etc., harmonics. However, harmonic generation may adversely affect the distribution system in other ways, e.g., interfere with powerline communications.

Higher third harmonics will cause larger currents in the neutral, and larger circulating currents will cause larger power losses. To compensate, the neutral wire will have to be larger to carry the additional current. Designers and users of these ballast systems may have to choose between ballast cost and wiring cost.

HIGH-PRESSURE SODIUM VAPOR BALLASTS

Unlike solid-state fluorescent ballasts, the HPS solid-state ballasts are not widely available. LBL obtained its test ballasts by submitting a special order, specifying for a particular lamp size. The limited number of suppliers makes comparison of the various solid state ballasts difficult because each ballast has been designed to operate a different size HPS lamp. ANSI has not developed comprehensive specifications for HID core-coil ballasts as it has for the fluorescent ballasts.

Efficacy

Efficacy increase in solid-state HPS systems results from their increased efficiency over core-coil ballasts. HPS lamps are not more efficacious when operated at high frequency. This result is reflected in results from the ballast 4 tests, shown in Table 5-4. Ballast 4 is a solid-state system that drives the lamp at 60 Hz with a square wave. The efficacy improvements are the same as for other ballasts that drive the lamps at high frequency. The 13% relative increase for ballast 2 results because its efficacy was compared with a well-regulated core-coil ballast that was less efficient than the other core-coil ballasts.[8]

Operation of HPS lamps at high frequency virtually eliminates the very high percent flicker. Note that ballast 4, operating lamps with a square wave at 60 Hz, still produces substantial flicker. Their reduced flicker makes these systems more attractive for industrial applications where some tasks involve rapidly rotating and moving machinery.

STATIC CONTROLS

Two-Lamp, F-40, Rapid-Start

Static controls are designed to be connected at either the input or the output side of standard rapid-start two-lamp fluorescent ballast. Their primary application is to reduce light output from systems that overilluminate. These systems dim both lamps equally in a fixture so that the fixture output maintains uniformity. Units that reduce light levels either 30 or 50% are available. The measurements made in this study evaluate the units' intrinsic performance. That is, the parameters are measured in a strip-type fixture (open-air) under ANSI conditions (room ambient 77°F, 25°C). Thus, the lamp wall temperature will be within ±5°F when measured with or without the static controllers. Under these conditions, efficacy does not increase when the system is operated with static controllers; other parameters remain the same. Unit efficacy that did increase 2 to 4% did so at the expense of reduced power factor and by lowering filament voltage. The reduced filament voltage at the lower light levels tends to reduce lamp life.

In an actual installation, the thermal environment can result in larger efficacy changes. If the lamps are installed in a four-lamp fixture that operates at lamp wall temperatures above 50°C, controls that reduce light output will also reduce the lamp wall temperature. Since the F-40 lamp system operates best at 40°C, reducing the lamp wall temperature from above 50°C toward 40°C will increase system efficacy. If the initial lamp wall temperature is 40°C, operating the lamps in a cool fixture, e.g., a two-lamp airhandling fixture, would reduce lamp wall temperature and lower light output. The latter application would reduce system efficacy. However, both these changes are fixture effects and do not result from the devices' intrinsic performance.

Because these systems are generally used for retrofit application, minimizing installation cost is important. Most of the above systems are hard-wired in the ballast compartment, an operation similar to replacing a ballast and costing about the same, typically $10-$15 per unit installation. Some of the units are designed to be installed between the lamp and the lamp socket. Costs for installing these units are less, but this type of device is not suitable for all types of fixtures.

F-96, Instant-Start

These static controllers reduce the light output of the 8-ft, F-96, instant-start lamp. This lamp's filament design differs from that of the F-40, rapid-start lamp. The rapid-start lamps heat the filament externally to ease the emission of electrons. The instant-start lamp's electrodes are heated solely from the lamp current plasma and ion bombardment, which simplifies the static controller design because no special provisions are required to maintain filament voltage when the power to the ballast is reduced.

Similar to the F-40 systems, the F-96 static controller changes system efficacy only slightly. The measured decrease in efficacy of system #10 can be attributed to reduced electrode heating due to the reduced arc current, which requires more voltage at the cathode. Note that this system reduces light output the most and operates lamps at the lowest current.

These controllers reduce lamp life because they operate the lamps at lower power. The increased sputtering at the lamps' ends also increases lumen depreciation. Researchers do not expect either of these effects to be severe.

DYNAMIC CONTROLS

Some dynamic control systems can dim fluorescent lamps continuously. These devices operate standard core-coil ballast systems by conditioning the input power to one ballast or a large group of ballasts. Solid-state ballasts have features that dim fluorescent lamps by means of low-voltage signals; these ballasts do not switch or condition the power supply.

Core-Coil Ballast Systems

The add-on dynamic devices are designed to control one or two two-lamp F-40, rapid-start lamp/ballast systems (device 1) in Table 5-7 or a large bank of lamps (devices 2 and 3), as shown by their current rating of 16 and 20A. However, all system performances have been tested with a single two-lamp F-40, T-12, rapid-start core ballast; testing the 16- and 20-A systems fully loaded was not practical.

One of the systems (3) could dim the lamps to 10% of full light output. However, the system could only do so with one two-lamp ballast. Whether the system could achieve this dimming range if it were fully loaded, i.e., operating 20 two-lamp ballasts, is uncertain. In addition, device 3 reduces filament power, and at 10% of full light output, it would probably reduce lamp life considerably. These test results indicate that systems operating large banks of lamps have an effective dimming range down to 50% of full light output.

Device 1 is designed to operate one two-lamp F-40 ballast and can dim lamps down to 33%. Tests of lamps operated at the lowest light output with full filament power gave no evidence of lamp failure. However, the results must be viewed with some reservation because only three units were tested. Lamps operated at low light output without the filament power lasted only 100 to 300 h.[9] These data indicate that removing filament power at lower light outputs may adversely affect lamps when they are operated at less than 50% of full light output.

Solid-State Ballasts

Solid-state ballast dimming systems can dim fluorescent lamps below 10% of full light output. At very low light levels, the filament voltage is still above the minimum ANSI specification. Unpublished results of tests on a few fluorescent lamps at low light levels with these ballasts show no decrease in lamp life.[10] These solid-state ballasts decrease power factors only slightly. Solid-state ballast system efficacy exceeds that of the standard core-coil system above 58% of full output. System efficacy is less below 58% of full light output. However, the number of hours the systems will operate above 58% output will exceed the operation time at low light levels. In any event, the power decreases over the entire range, and the solid-state ballast dimming systems can save more energy than core-coil dimming systems by virtue of their high efficacy and greater dimming ranges.

ELECTROMAGNETIC COMPATIBILITY

LBL measured solid-state ballast and add-on controller broad band conducted and radiated EMI. The narrow band radiated value is measured at the peak of the fundamental frequency at which the lamp is driven, between 20 and 30 kHz. Solid-state conducted and radiated EMI exceeds that of the 60-Hz core-coil ballasted systems.[4,5] Field tests of similar systems in buildings with 50- to 500-ballast installations have reported no interference with existing office equipment. Very sensitive medical diagnostic equipment that measures low-voltage signals[5] was affected by both the standard core-coil ballasts and the solid-state ballast systems. LBL measured solid-state ballasts that exhibited no excessive EMI. EMI measured for add-on control devices and static controllers was the same as that measured for the core-coil ballast system. However, users are still concerned about interference, and the lighting industry is attempting to determine permissible EMI levels.[11]

Section 7

SUMMARY

The devices tested in this study represent the vanguard of new technologies for lighting products. They promise to provide the largest improvement in system efficacy and in the effective use of lighting. Together they can reduce energy use by 50 to 70%, depending on the application,[12] which can significantly decrease the demand for electric power during the peak demand hours, increase load factor, and reduce the need for new generating capacity. LBL restricted its study of solid-state ballast systems to systems that are on the market. The study did not include some units that have just been approved by Underwriters Laboratory and will soon be available. Although the solid-state ballasts are designed to operate both standard F-40 (40-W) and energy-saving F-40 (34-W) fluorescent lamps, LBL measured only the standard F-40, 40-W lamps. Future research should measure ballast performance with the energy-saving 34-W lamps, including ballast factor and thermal performance.

SOLID-STATE BALLASTS

The tested solid-state ballasts varied widely in input power, light output, and ballast factor. System efficacy varied little for the dedicated ballasts and lamps, which provide about 80 lm/W. The ballast factor, application, and thermal environment will determine which system has the greatest advantage over a standard core-coil ballasted system. Ballast manufacturers' specifications generally give electrical engineers information for determining the required wire size; i.e., catalog data indicate the type of lamp the ballast will operate (the input voltage, current, and power). The information in this report, which has not been readily available, should help end users and designers determine the best system for a particular application.

Fluorescent lamp/ballast systems that met ANSI standards allowed engineers to design lighting systems with the CBM ballast and F-40 fluorescent lamps from experience, and obtain predictable light levels. Today, no ballast performance is set by ANSI standards if a ballast is used with an energy-saving lamp, because no standards exist for these systems.

LBL obtained some solid-state test ballasts from firms that have been producing them since 1979. Manufacturing techniques and quality have improved so that ballast infant mortality rates are below 1%. Some of the tests in this study (thermal performance, open-circuit voltage) can determine design ruggedness, but actual installations must be evaluated to obtain complete information on product life.

STATIC CONTROLS

Static controls, applicable primarily as retrofits in overilluminated spaces, are generally reliable, and selection is based on equipment and installation costs. Some manufacturers have claimed that these systems greatly increase efficacy. LBL found no improvement in system efficacy when the lamps are operated at the same lamp wall temperature. Researchers did measure a 2-4% increase on systems that operated lamps at a lower filament power and reduced power factor. In addition to static controls, users can consider other methods of reducing light output, e.g., delamping, phantom tubes, energy-saving lamps, and (core-coil or solid-state) ballasts.

DYNAMIC CONTROLS

New dynamic controls include devices that control standard core-coil ballasts over a wide range, as well as solid-state ballasts specifically designed to control fluorescent lamps by low-voltage signals. The add-on controllers, which control large banks of lamps, are most suitable for retrofits because they can be installed in the electric closet. The cost may be as low as $12 to $16 per ballast. However, these installations limit the control strategies.[12] Solid-state ballasts can use all control strategies and maximize energy savings. However, because they must be installed in each fixture, their application is best limited to renovations or new construction.

The results of this study provide a guide for recommending the most suitable product for a particular application. The report clearly indicates the important parameters in lighting design, product reliability, and cost-effectiveness. Manufacturers should supply this information and end users should require it.

Section 8

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